Edge Effects and Spatial Frequency Analysis in Metacontrast

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EDGE EFFECTS AND SPATIAL FREQUENCY
ANALYSIS IN METACONTRAST

by
Ronald L. Growney

A Dissertation Submitted to the Faculty of the Graduate School
of Loyola University of Chicago in Partial Fulfillment
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VITA

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>ii</td>
</tr>
<tr>
<td>VITA</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
</tbody>
</table>

## Chapter

### I. CONTOUR INFORMATION AND APPARENT BRIGHTNESS

- Edge Effects and Apparent Brightness: 4
- The Function of Contour Information in Perceptual Processing: 7
- Metacontrast and Edge Effects: 13
- Hypotheses Regarding the Function of Edges in Metacontrast: 22
- Hypotheses Regarding the Temporal Characteristics of Metacontrast: 28

### II. SPATIAL FREQUENCY ANALYSIS AND APPARENT BRIGHTNESS

- Spatial Frequency Analysis and Detection: 35
- Spatial Frequency Analysis and Apparent Brightness: 42
- The Function of a Frequency Coding in Visual Processing: 49
- Metacontrast and a Spatial Frequency Transformation: 52
- Contour Information and High Spatial Frequency Analysis: 55
- Hypotheses Regarding a Spatial Frequency Analysis: 56
- Models of Information Processing: 61
  - Model 1: 62
  - Model 2: 62
  - Model 3: 63

### III. METHOD

- The Stimuli: 64
- Construction of the Stimuli: 66
- Observers: 85
- Procedure: 86
# TABLE OF CONTENTS Continued

<table>
<thead>
<tr>
<th>Chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Method Continued</strong></td>
</tr>
<tr>
<td>Response Measure ........................................... 88</td>
</tr>
<tr>
<td>The Correspondence of Magnitude Estimations to Values of Luminance ............................. 90</td>
</tr>
<tr>
<td>The Transfer Characteristics of Peripheral Visual Processing ........................................... 93</td>
</tr>
<tr>
<td>Comparison of the Apparent Brightness of the Stimuli .................................................. 102</td>
</tr>
<tr>
<td>Comparison of the Contrast of the Stimuli ................................................................. 107</td>
</tr>
</tbody>
</table>

| IV. RESULTS FOR THE EDGE HYPOTHESES. ........................................................................ 112 |
| General Characteristics of the Data ............................................................................. 113 |
| Examination of the Target-Mask Interaction ............................................................. 134 |
| Models of Edge Activity in Metacontrast ................................................................. 144 |
| Temporal Effects as a Function of Luminance Gradients ........................................... 161 |

| V. RESULTS REGARDING A SPATIAL FREQUENCY ANALYSIS IN METACONTRAST. .......... 163 |
| General Characteristics of the Data ............................................................................. 168 |
| Comparison of the Masking Amplitudes of the Edge Gradient and Frequency Stimuli .... 184 |
| Comparison of the Frequency Data to Models of Edge Activity in Metacontrast ........ 185 |
| The Effects of the Transfer Characteristics of the Optics of the Eye ....................... 192 |
| Correspondence of the Data to Models of Spatial Frequency Interaction ................ 194 |
| Temporal Characteristics of the Data ............................................................................ 219 |

<p>| VI. DISCUSSION .................................................................................................................. 225 |
| Metacontrast and Contour Information ......................................................................... 225 |
| Metacontrast and Frequency Coding ............................................................................. 233 |
| Contour Information as High Spatial Frequency Information ...................................... 240 |
| Metacontrast and the Contrast of Masking Stimuli ...................................................... 241 |
| Other Hypotheses of the Function of Edge Information in Metacontrast .................. 243 |
| Metacontrast and Form Similarity .................................................................................. 248 |</p>
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>VII. CONCLUSION</td>
<td>251</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>256</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.</td>
<td>Analytical functions describing the luminance distributions of each of the five targets.</td>
</tr>
<tr>
<td>2.</td>
<td>Analytical functions describing the luminance distributions of each of the 43 masks.</td>
</tr>
<tr>
<td>3.</td>
<td>Stimuli transmittances as a function of the transmittance of the layers comprising the final stimulus</td>
</tr>
<tr>
<td>4.</td>
<td>Summary of the transmittance (in percent) and corresponding values of luminance (in footlamberts) for each of the stimuli.</td>
</tr>
<tr>
<td>5.</td>
<td>Equations describing the relationship of magnitude estimations, $B$, to luminance, $L$, for each observer.</td>
</tr>
<tr>
<td>6.</td>
<td>Magnitude estimations of the apparent brightness of each stimulus by observer 1, $O_1$, and observer 2, $O_2$.</td>
</tr>
<tr>
<td>7.</td>
<td>Pairwise comparisons of the ratings of apparent brightness of each stimulus by observer 1, $O_1$, and observer 2, $O_2$, using the Wilcoxon Matched-Pairs, Signed-Ranks test.</td>
</tr>
<tr>
<td>8.</td>
<td>Values representing the greatest amount of masking for each target-mask combination at $1'$ separation for the data of the two observers.</td>
</tr>
<tr>
<td>9.</td>
<td>Normalized, inverted values representing the greatest amount of masking for the data shown in Table 8.</td>
</tr>
<tr>
<td>10.</td>
<td>The data representing the greatest amount of masking for each stimulus combination at target-mask separations of $1'$ and $12'$ of visual angle for the data of the two observers.</td>
</tr>
<tr>
<td>11.</td>
<td>Product of the maximum/minimum ratios for each target-mask combination for (a) $2'$ and (b) $4'$ of visual angle about the edge of each stimulus.</td>
</tr>
<tr>
<td>12.</td>
<td>ISIs in milliseconds at which the greatest amount of masking occurred for the first three</td>
</tr>
<tr>
<td>Table</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>target-mask separations in minutes of visual angle for observer 1, O1, and observer 2, O2</td>
<td>166</td>
</tr>
<tr>
<td>ISIs in milliseconds at which the greatest amount of masking occurred for the first three target-mask separations in minutes of visual angle for observer 1, O1, and observer 2, O2</td>
<td>167</td>
</tr>
<tr>
<td>Peak masking data for the frequency stimuli, normalized with respect to the datum of each observer, O1 and O2, for the Gate target-Batman mask combination of stimuli</td>
<td>190</td>
</tr>
<tr>
<td>Measures of channel bandwidth with frequency limits A and B in degrees for (a) a narrow channel, to first zero on either side of the center frequency, and (b) a wider channel to second zero on either side of the center frequency</td>
<td>204</td>
</tr>
<tr>
<td>Results of the cross-correlation of the frequency spectra of the target and mask at 1' separation over the frequency range from 0 to 25 c/d</td>
<td>210</td>
</tr>
<tr>
<td>Ranking of masks in terms of ISI for which peak masking was obtained for each target for observer 1, O1, and observer 2, O2, from longest to shortest</td>
<td>221</td>
</tr>
<tr>
<td>ISI in milliseconds at which the greatest amount of masking occurred for each target-mask combination for separations of 1', 4', and 12'</td>
<td>224</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.</td>
<td>The results of O'Brien's experiment.</td>
</tr>
<tr>
<td>2.</td>
<td>Apparent brightness as a function of enhanced contour.</td>
</tr>
<tr>
<td>3.</td>
<td>The output of a lateral inhibition system as a function of input which differ in average luminance</td>
</tr>
<tr>
<td>4.</td>
<td>Subjective pattern and contour</td>
</tr>
<tr>
<td>5.</td>
<td>Luminance distributions of the stimuli which differ primarily in edge gradient.</td>
</tr>
<tr>
<td>6.</td>
<td>Hypothesized excitatory, E, and inhibitory, I, components illustrating Weisstein's (1968) two-factor theory of metacontrast.</td>
</tr>
<tr>
<td>7.</td>
<td>Relation of neural rise time corresponding to the mask to the interstimulus interval (ISI) for which peak masking occurs in Weisstein's two-factor theory.</td>
</tr>
<tr>
<td>8.</td>
<td>Relation of neural rise time corresponding to the target to the interstimulus interval (ISI) for which peak masking occurs in Weisstein's two-factor theory.</td>
</tr>
<tr>
<td>9.</td>
<td>Luminance distribution of a frequency-modulated gate stimulus.</td>
</tr>
<tr>
<td>10.</td>
<td>The basic pattern (transparency), the image of which is swept horizontally across film.</td>
</tr>
<tr>
<td>11.</td>
<td>Apparatus for constructing the stage 1 negatives.</td>
</tr>
<tr>
<td>12.</td>
<td>Approximate transfer characteristics of the slide negative and of the tachistoscope lens.</td>
</tr>
<tr>
<td>13.</td>
<td>Construction of the 2.5 c/d mask at a given target-mask separation.</td>
</tr>
<tr>
<td>14.</td>
<td>The relationship of the magnitude estimations to luminance for the ratings of the two observers.</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES Continued**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.</td>
<td>Transfer of characteristics of the optics of the eye.</td>
<td>96</td>
</tr>
<tr>
<td>16.</td>
<td>Magnitude estimations of the contrast of the frequency-modulated stimuli for the two observers.</td>
<td>108</td>
</tr>
<tr>
<td>17.</td>
<td>Magnitude estimations of the Sine R target with the Sine R mask as a function of temporal interstimulus interval (ISI).</td>
<td>114</td>
</tr>
<tr>
<td>18.</td>
<td>Magnitude estimations of the Sine R target with the Sine A mask as a function of temporal interstimulus interval (ISI).</td>
<td>115</td>
</tr>
<tr>
<td>19.</td>
<td>Magnitude estimations of the Sine R target with the Gate mask as a function of temporal interstimulus interval (ISI).</td>
<td>116</td>
</tr>
<tr>
<td>20.</td>
<td>Magnitude estimations of the Sine R target with the Batman mask as a function of temporal interstimulus interval (ISI).</td>
<td>117</td>
</tr>
<tr>
<td>21.</td>
<td>Magnitude estimations of the Sine A target with the Sine R mask as a function of temporal interstimulus interval (ISI).</td>
<td>118</td>
</tr>
<tr>
<td>22.</td>
<td>Magnitude estimations of the Sine A target with the Sine A mask as a function of temporal interstimulus interval (ISI).</td>
<td>119</td>
</tr>
<tr>
<td>23.</td>
<td>Magnitude estimations of the Sine A target with the Gate mask as a function of temporal interstimulus interval (ISI).</td>
<td>120</td>
</tr>
<tr>
<td>24.</td>
<td>Magnitude estimations of the Sine A target with the Batman mask as a function of temporal interstimulus interval (ISI).</td>
<td>121</td>
</tr>
<tr>
<td>25.</td>
<td>Magnitude estimations of the Gate target with the Sine R mask as a function of temporal interstimulus interval (ISI).</td>
<td>122</td>
</tr>
<tr>
<td>26.</td>
<td>Magnitude estimations of the Gate target with the Sine A mask as a function of temporal interstimulus interval (ISI).</td>
<td>123</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>27.</td>
<td>Magnitude estimations of the Gate target with the Gate mask as a function of temporal inter-stimulus interval (ISI).</td>
<td>124</td>
</tr>
<tr>
<td>28.</td>
<td>Magnitude estimations of the Gate target with the Batman mask as a function of temporal inter-stimulus interval (ISI).</td>
<td>125</td>
</tr>
<tr>
<td>29.</td>
<td>Magnitude estimations of the Batman target with the Sine R mask as a function of temporal inter-stimulus interval (ISI).</td>
<td>126</td>
</tr>
<tr>
<td>30.</td>
<td>Magnitude estimations of the Batman target with the Sine A mask as a function of temporal inter-stimulus interval (ISI).</td>
<td>127</td>
</tr>
<tr>
<td>31.</td>
<td>Magnitude estimations of the Batman target with the Gate mask as a function of temporal inter-stimulus interval (ISI).</td>
<td>128</td>
</tr>
<tr>
<td>32.</td>
<td>Magnitude estimations of the Batman target with the Batman mask as a function of temporal inter-stimulus interval (ISI).</td>
<td>129</td>
</tr>
<tr>
<td>33.</td>
<td>Greatest masking values (peak masking) at a particular ISI as a function of target-mask separation for the Gate target with various masks</td>
<td>133</td>
</tr>
<tr>
<td>34.</td>
<td>Normalized values representing the greatest amount of masking (peak masking) for the inverted data at a target-mask separation of 1' for a given target for the four masks</td>
<td>138</td>
</tr>
<tr>
<td>35.</td>
<td>Normalized values representing greatest amount of masking (peak masking) for the inverted data at target-mask separation of 1' for a given mask for the four targets</td>
<td>143</td>
</tr>
<tr>
<td>36.</td>
<td>Normalized areas describing stimulus luminance within x minutes of the edge of the stimulus for several values of x.</td>
<td>146</td>
</tr>
<tr>
<td>37.</td>
<td>The same as Figure 36 except the normalized areas describe the logarithm of stimulus luminance within x minutes of the edge of the stimulus</td>
<td>143</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>33.</td>
<td>Normalized, straight-line approximation to the weighting function for a Gate target, 49' in width, averaged over the results of the three observers from Growney and Weisstein, 1972.</td>
<td>152</td>
</tr>
<tr>
<td>39.</td>
<td>Normalized areas describing the convolution of the weighting function with the stimulus functions within x minutes of the edge of the stimulus for x and the masks described as in Figure 36.</td>
<td>153</td>
</tr>
<tr>
<td>40.</td>
<td>Comparison of the data of the two observers with the convolution of the weighting function and stimulus function for two limit values of visual angle within each mask for the Gate target.</td>
<td>154</td>
</tr>
<tr>
<td>41.</td>
<td>Comparison of the data with the convolution of the line spread function (Campbell, Carpenter, &amp; Levinson, 1969) and the stimulus functions over 4' of visual angle within each target for the Batman mask.</td>
<td>160</td>
</tr>
<tr>
<td>42.</td>
<td>ISIs in milliseconds at which the greatest amount of masking occurred for each mask, averaged across targets.</td>
<td>163</td>
</tr>
<tr>
<td>43.</td>
<td>ISIs in milliseconds at which the greatest amount of masking occurred for each target, averaged across masks.</td>
<td>164</td>
</tr>
<tr>
<td>44.</td>
<td>Magnitude estimations of the Gate target with the Gate mask as a function of temporal interstimulus interval (ISI).</td>
<td>170</td>
</tr>
<tr>
<td>45.</td>
<td>Magnitude estimations of the Gate target with the 2.5 c/d mask as a function of temporal interstimulus interval (ISI).</td>
<td>171</td>
</tr>
<tr>
<td>46.</td>
<td>Magnitude estimations of the Gate target with the 5 c/d mask as a function of temporal interstimulus interval (ISI).</td>
<td>172</td>
</tr>
<tr>
<td>47.</td>
<td>Magnitude estimations of the Gate target with the 10 c/d mask as a function of temporal interstimulus interval (ISI).</td>
<td>173</td>
</tr>
</tbody>
</table>
LIST OF FIGURES Continued

Figure | Page
--- | ---
43. | Magnitude estimations of the Gate target with the 15 c/d mask as a function of temporal interstimulus interval (ISI). 174
49. | Magnitude estimations of the 5 c/d target with the Gate mask as a function of temporal interstimulus interval (ISI). 175
50. | Magnitude estimations of the 5 c/d target with the 2.5 c/d mask as a function of temporal interstimulus interval (ISI). 176
51. | Magnitude estimations of the 5 c/d target with the 5 c/d mask as a function of temporal interstimulus interval (ISI). 177
52. | Magnitude estimations of the 5 c/d target with the 10 c/d mask as a function of temporal interstimulus interval (ISI). 178
53. | Magnitude estimations of the 5 c/d target with the 15 c/d mask as a function of temporal interstimulus interval (ISI). 179
54. | Peak magnitude estimations for each target-mask combination at a separation of 1' for the data of the two observers. 131
55. | Normalized areas describing the amount of luminance within x minutes of the edge of the stimulus for several values of x. 187
56. | Comparison of the data of observer 2 for the 5 c/d target with the amount of luminance with 2' of the edge of the mask. 137
57. | Normalized areas describing the amount of weighted luminance within x minutes of the edge of the stimulus. 139
58. | Data corrected for the amount of weighted luminance within 4' of the stimulus edge for observer 1 and 3' of the stimulus edge for observer 2. 202
59. | Comparison of the uncorrected data to the contrast ratings of the masking stimuli. 206
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.</td>
<td>Normalized areas describing the results of the cross-correlation of the frequency spectra of</td>
<td>211</td>
</tr>
<tr>
<td></td>
<td>the mask for a (a) narrow bandwidth and a (b) wider bandwidth about several center frequencies.</td>
<td></td>
</tr>
<tr>
<td>61.</td>
<td>Target-Mask ratios of areas beneath the frequency spectra of the stimuli within a narrow</td>
<td>213</td>
</tr>
<tr>
<td></td>
<td>bandwidth about several center frequencies.</td>
<td></td>
</tr>
<tr>
<td>62.</td>
<td>Mask/Target ratios of areas beneath the frequency spectra of the stimuli as for Figure 61.</td>
<td>219</td>
</tr>
<tr>
<td>63.</td>
<td>ISI in milliseconds at which peak masking occurred for each target-mask combination at</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>a target-mask separation of 1'.</td>
<td></td>
</tr>
</tbody>
</table>
INTRODUCTION

This study has been conceived and analyzed from a particular perspective. This point of view is that the visual perceptual process by which we perceive the world consists of a series of transformations by brain mechanisms upon the neural code corresponding to the stimulus object. A basic task of pattern recognition theory, then, is to specify these transformations or the transfer characteristics of these brain mechanisms which, together, accept the visual stimulus as input and yield the perception of form as output. These transformations remain, for the most part, unspecified. Transformations which occur early in the perceptual process are thought to involve (1) the initial registration of the energy array corresponding to the stimulus object by receptor mechanisms and the transduction of this energy information into some neural code; and (2) the summarization or description of the stimulus pattern which might involve the abstraction of features or relational characteristics corresponding to the stimulus pattern from properties of the neural code or might involve a transformation upon the neural code which could correspond, for example, to a fourier analysis of the original stimulus luminance distribution. Transformations which occur later in the perceptual process are thought to involve interpretive operations which accept the output of earlier descriptive stages and use the coded description corresponding to the visual stimulus within a framework of how
the world is supposed to look (Neisser, 1967; Pribram, 1971; Weisstein, 1971; Arbib, 1972).

The purpose of this study is to investigate the properties of two possible transformations which may be involved in the early stages of stimulus description during the pattern recognition process. There is evidence suggesting that: (1) contour information, information due to the edges of patterned stimuli, is particularly important in affecting the apparent brightness of stimuli, and (2) the visual system may analyze patterned stimuli in terms of their spatial frequencies or, at least, perform a transformation on stimulus input which is proportional to the Fourier coefficients of the stimuli. It is not known how these factors function in the pattern recognition process. It is not clear, for example, whether or not information about contours is identical to information about high spatial frequencies in neural processing. Such information is equivalent in the stimulus pattern. However, this information may be used in different ways at different stages of the neural processing of information about the stimulus.

The study tests hypotheses about the uses of contour information and spatial frequency information in neural processing by investigating the target-mask interaction in a metacontrast experiment.
CHAPTER I

CONTOUR INFORMATION AND APPARENT BRIGHTNESS

In the search for possible features of the visual stimulus which might be abstracted early in the perceptual process, edges or the contours of stimulus objects have seemed likely candidates (e.g., Dodwell, 1970; Haber & Hershenson, 1973; Uhr, 1973). Phenomenally, the edges of an object serve to segregate the object as a figure separate from the background and seem to belong to the object (Hochberg, 1971). Shapes are usually areas of the visual field that are set off from the rest of the field by a visible contour, although a contour is only a sufficient, not a necessary, condition for the perception of form. If the brightness-difference contour between two regions is blurred so that the luminance of one region shades off gradually into the luminance of the other region, the shapes of both are perceived as indefinite (O'Brien, 1958).

Edges or contours occur with a relatively abrupt change of the spatial luminance gradient which describes the patterned luminance of a stimulus (mathematically, it's the change of the change, that is, the second derivative of luminance, which is large at an edge; see Ratliff, 1965). The information provided by the luminance change at an edge seems to have a special significance in the way in which it is processed by the nervous system, over and above the fact that a particular group of retinal cells have been stimulated. Fry and Bartley (1935),
for example, found that the neural unit(s) stimulated by a contour exerts an inhibitory influence on the threshold of neural units stimulated by neighboring parallel contours and an enhancing effect on the threshold of neural units stimulated by perpendicular contours.

**Edge Effects and Apparent Brightness**

Edges have been shown to be particularly influential in the determination of the apparent brightness of stimuli. O'Brien (1958), for example, has demonstrated that the kind of transition (contour) between two areas of stimulus luminance determines the apparent-brightness relationship of the two areas. A gradual change in physical intensity between two areas results in one uniformly-bright area with no apparent evidence of any intensity change (Figure 1a). A sharp step in luminance, on the other hand, will produce a sharp step in apparent brightness corresponding to the difference in stimulus luminance between the two areas, and characteristic Mach bands will be present. The importance of an edge is shown dramatically in Figure 3 of the article by Land and McCann (1971). With an edge present the difference in apparent brightness between two areas is unmistakable. If the edge is covered by a pencil so that the two areas are no longer separated by a single, sharp edge, however, the two areas look uniformly bright and indistinguishable.

The effects of enhanced contours on apparent brightness
are even more remarkable. O'Brien constructed a stimulus such that an enhanced dark edge was adjacent to the darker of two areas of different luminance, with a gradual slope of increasing intensity into the area of higher luminance (Figure 1b). The apparent brightness experience of the observer is that the brighter of the two areas corresponds to the area of smaller luminance, a reversal of the usual correspondence between the

![Graph (a)](image1)

![Graph (b)](image2)

**Fig. 1.** The results of O'Brien's experiment. (a) A gradual change in luminance, $L$, across space, $x$, corresponds to a uniform apparent brightness distribution, $B$. (b) An enhanced luminance contour (shown on the left) yields a distribution of apparent brightness (shown on the right) opposite in amplitude to that of the luminance distribution.

amplitude of the luminance distribution and the relative amplitude of the apparent brightness distribution. Cornsweet (1970) has described a similar phenomenon (Figure 2a). The presence
of an adjacent trough and peak (enhanced contour) in an otherwise level luminance distribution will result in a difference in apparent brightness between the areas on either side of the edge, with the apparently darker area on the trough side of the edge. Cornsweet's phenomenon has been extended by Arend, Buehler, and Lockhead (1971). Arend et al. placed several enhanced contours in a level intensity distribution and obtained a staircase of decreasing apparent brightness, one step for each edge (Figure 2b).

Fig. 2. Apparent brightness as a function of enhanced contour. (a) O'Brien-Cornsweet effect. An enhanced contour in a level luminance distribution, L, with respect to space, x, yields two areas of different apparent brightness, B. (b) Extension of the effect to multiple contours by Arend et al.
The Function of Contour Information in Perceptual Processing

Bekesy (1960) has suggested that the simplest of the edge effects, the Mach bands (see also Ratliff, 1965), may be obtained due to lateral inhibition in the visual system. In particular, these lateral effects can be described concisely by a weighting function with an inhibitory radius corresponding to 10' of visual angle and an excitatory center which is small in width compared to the width of the inhibitory surround. This weighting function describes the visual system as a whole; stimulus luminance magnitude is the input to the system (the black box) and apparent brightness magnitude is the output.

One interpretation of the function of edge information such as that provided by the Mach bands is that the bands restore and enhance the luminance gradient which is blurred due to the poor optics of the accessory eye system. Lateral inhibition, according to this view, plays a fundamental role in the rectification of blurred contours (Ratliff, 1965). This conclusion has been disputed. Campbell and Gubisch (1966) argue that if compensation due to lateral inhibition were occurring in the visual system, then human contrast sensitivity should parallel the contrast transmission of an ideal optical system for spatial frequencies. A comparison of contrast sensitivity data with relative contrast transmission data (actual/ideal) shows that the visual system compensates for spatial frequencies up to 10 cycles per degree (sensitivity increases in this range) and undercompensates at high spatial frequencies (sensitivity decreases
rapidly above 10 cycles/degree). Because the visual system undercompensates for high spatial frequencies, where most edge information should be concentrated, Campbell and Gubisch, after Mach (1865) and Barlow (1961), suggest that the heightened contrast at the borders of stimuli is only a by-product of the output of a lateral-inhibition system; the primary function of such a system may be to make visual sensation independent of average illumination. For example, suppose that the weighting function shown in Figure 3 is a composite description of the visual system; this weighting function, then, represents the characteristics of the cascade of neural mechanisms which accept luminance as input and yield perceptual response as output. If the weighting function is applied to the stimulus distributions shown in Figures 3b and 3d, the resulting output is shown in Figures 3c and 3e. In each case (Figure 3b and 3d), the average illumination is different, but the average output is the same. This is a particular example which is true because the total excitation and inhibition in the weighting function are equal (see Bekesy, 1960). In this case, visual sensation is independent of average illumination. This is not true if excitation and inhibition are not equal; for this latter case Ratliff's (1965) interpretation that contour enhancement is of primary importance seems the more valid hypothesis.

Although a lateral-inhibition system does make visual sensation independent of average illumination if excitation
Fig. 3. The output of a lateral inhibition system as a function of input which differ in average luminance. (a) A hypothetical weighting function describing the composite lateral inhibition characteristics of the visual system. Total excitation equals inhibition. \( \Theta \) denotes the magnitude of the weights at each point along a horizontal dimension, \( x \), in space. \( \Theta = 0 \) denotes the level of background noise. (b) and (d) Two distributions of stimulus luminance, \( L \), in space, \( x \), which differ in average luminance. (c) and (e) corresponding apparent brightness output, \( B \), for the luminance distributions above.

and inhibition are equal, edge information could still be of special importance in determining apparent brightness. In fact, the data from studies of enhanced contour stimuli suggest that
this is the case. The introduction of contour into a level luminance distribution changes the apparent brightness experience corresponding to the luminance distribution. These changes are not confined locally to the contour (e.g., O'Brien, 1953). Further, contour enhancement does occur as shown by indirect measures of human visual transfer characteristics (Patel, 1966; Hay & Chesters, 1970; 1972). Such preprocessing as neural sharpening could be very important in preparing input to edge mechanisms, on the assumption that such mechanisms exist. Assume, then, that edge information is of special significance to the visual system, and that a lateral-inhibition system performs two functions simultaneously: (1) lateral inhibition makes visual sensation independent of average illumination, and (2) it enhances (sharpens) the luminance gradient at contours, a preprocessing which would make edge information a more effective input to some mechanism within the visual system which would yield apparent brightness as output.

A weighting function describing a lateral-inhibition system predicts correctly the apparent brightness output of Mach bands (Bekesy, 1960). Davidson and Whiteside (1971), however, demonstrate several qualitative differences between the effects predicted by the weighting function and obtained judgements of apparent brightness resulting from different types of steps in luminance. They point out that no choice of modulation transfer function, and, therefore, its inverse Fourier transform (the weighting function) can account for the illusions
of Cornsweet or O'Brien. Changes in apparent brightness of a stimulus because of visual transfer characteristics are relatively local with respect to changes in stimulus luminance. Brightness differences at some distance from the edge, therefore, are puzzling. Davidson and Whiteside suggest that subsequent to the application of a weighting function there may be a brightness integrating mechanism. The effect of this mechanism is to make the apparent brightness of a particular bar in a grating directly proportional to the integral of the convolution of the stimulus luminance distribution and the weighting function for that particular bar. This hypothesis can account qualitatively for Cornsweet's illusion, at least over small areas. The integral on either side of the edge will be influenced differentially. One side of the edge will be influenced by a positive maximum on that side of the edge, while the integral over the area on the other side of the edge will be influenced by the negative minimum. This would predict a difference in apparent brightness on either side of the edge. The opposite relationship between stimulus luminance and apparent brightness obtained by O'Brien and by Arend et al. remain unexplained, however.

The weighting function hypothesis together with the integration hypothesis are insufficient to explain apparent brightness data. This is puzzling in view of the importance of edge information as suggested above by enhanced contour data.
Davidson and Whiteside found no connection between the amplitude of the maximum at the edge of a bar of the observed grating (obtained by convolving the spatial luminance distribution with the weighting function) and the apparent brightness of the bar. They found a much closer fit to the apparent brightness data by taking the integral across the weighted-luminance distribution of that bar; hence the integration hypothesis applies.

It is possible, however, that (1) Davidson and Whiteside found that edge effects are not predicted by the amplitude of the maximum at the stimulus edge because such a measure may be an insufficient measure of contour information (see below) and that (2) a prediction of apparent brightness based on a sufficient measure of contour information might yield a result which is proportional to the integral of the weighted-luminance distribution. Of the possible measures of contour information, a very interesting suggestion has been made by Land and McCann (1971).

Land and McCann have described a model of the function of edges in apparent brightness phenomena. They consider the problem first raised by Helmholtz. Although the flux stimulating the eye from part of a scene is the product of the reflectance of that part of the scene and the illuminance upon that part, the apparent brightness of that part of the scene may approximate the actual reflectance of the scene, depending on the surround. This approximation occurs even in nonuniform
illumination, the ambient illuminating condition. Land and McCann suggest that the visual system has evolved a mechanism to determine the reflectance of objects in a way that is independent of illuminance. Because of the importance of edges in apparent brightness, they suggest that a ratio of two sampled points on either side of an edge can give a number which closely approximates the ratio of reflectances of the two areas. The ratio of reflectance of any two areas in the visual field, contiguous or not, can then be obtained from the product of the ratios of reflectance for all edges between the two areas in question.

The computation of ratios is a calculation which could be performed readily by the visual system. Because there is a logarithmic transformation early in the visual pathway, even as early as the late receptor potential (Brown, 1963), the computation of ratios and products of ratios can occur whenever there is a summation of inhibition and excitation or a separate summation of inhibition and excitation, respectively. For example, suppose that there is a cell, R, late in the visual pathway which samples a small portion of light, as a slit, for its excitatory input, and has an extensive inhibitory surround. If the inhibitory surround consists of cells with similar excitatory input (slits), then the frequency of firing of cell R represents the ratio of the reflectance of the stimulus region sampled by the excitatory center of cell R to the reflectances of all the other stimulus regions sampled by
A suitable measure of contour information might be the reflectance ratio defined as follows. Assume that a weighting function, such as the function used by Campbell, Carpenter and Levinson (1969), is convolved with stimulus luminance at some stage in the visual pathway. For a stimulus which is a step in luminance, the result of the convolution would appear as above, in Figure 1b on the right. Assume further that the maximum (peak) and the minimum (trough) about the point corresponding to the edge are selected by the visual system for further information processing. The ratio of maximum to minimum is defined to be the reflectance ratio. It is this quantity which, by hypothesis, uniquely determines the brightness of an area lateral to the edge. This interpretation of the reflectance ratio is a specific model and so an extension of the hypothesis of Land and McCann. It is interesting in this regard that Campbell, Carpenter and Levinson (1969) used the maximum minus minimum quantity as their measure of threshold amplitude, with which they obtained agreement with linear predictions. A necessary condition for this model is that, once the ratio is defined as maximum/minimum, for example, all the edges in the visual field must be described similarly, not by the reciprocal of the ratio. The trough must always be represented in the denominator of the reflectance ratio; otherwise the edge effects are simply cancelled to unity. (This restriction is implicit in the treatment of Land & McCann.) To show how the reflectance ratio
with this restriction can predict brightness, the model will be applied to Cornsweet's phenomenon. If the reflectance ratio has the value (maximum/minimum) = 2/1, then the apparent brightness of the area on the trough side of the edge is 2/1 the apparent brightness of the area on the peak side of the edge (see Figure 2a). For the experiment of Arend et al., if each edge has the same reflectance ratio, say 2/1, then the apparent brightness of the area on the trough side of the first edge is 2/1 the apparent brightness of the first area; the area on the trough side of the second edge is 2/1 x 2/1 = 4/1 times the apparent brightness of the first area, and so on. The reflectance ratio can also predict the effects of O'Brien's experiment if it can be assumed that the maximum is simply a smaller number than the minimum. But this points out a basic problem with the application of Land and McCann's hypothesis to enhanced contour data. Why should the visual system compute apparent brightness using the reflectance ratio with respect to the trough side of the edge, or in terms of Figures 2a and 2b, applying the reflectance ratio from left to right? It could be important that for each case in Figures 1 and 2, that the area on the extreme left of each stimulus is a central disk while the areas on the right side of each edge are annuli about this central disk. One hypothesis is that the central disk is the only whole figure and that the integration of brightness takes place across it such that the central disk is
taken as the reference point for the computation of reflectance ratios. Certainly, an integration hypothesis such as that of Davidson and Whiteside is insufficient by itself to account even qualitatively for the difference in apparent brightness in the experiment of Arend et al. Each annulus contains a peak and a trough so that the sign of the integration would be the same for all of the annuli. But the difficulty of explaining how the reference point is chosen for computing apparent brightness based on the reflectance ratio still remains.

The models which relate contour information to apparent brightness, such as Davidson and Whiteside's (1971) or Land and McCann's (1971), have in common the task of first specifying a suitable measure of contour information and, second, of describing how this contour information changes or influences apparent brightness output. Part of the problem may be that contour information is only a sufficient condition for the perception of shape (e.g., Hochberg, 1971). An example of some other factors which contribute to the perception of form but which remain unspecified, are illustrated in Figure 4. One example in which the visual system generates or fills in a contour is shown in Figure 4a. The two halves of the figure appear to be separated by a vertical white stripe. A second example is shown in Figure 4b. Observers report seeing a figure, usually a circle, with defined edges in the center region of the four lines. Examples such as these suggest that the perception of form with well-defined contour may always be the
generative result of some brain mechanism. The input requirements of this mechanism may be quite general or, alternatively, there may be several mechanisms for each kind of input. In any case, real stimulus contours may be only one kind of input to a general mechanism which generates the perceived contour together with the segregated figure. If this is the case, the definition of contour information might have to include the factors which are common to the other, unspecified, factors which also contribute to the perception of form. The input requirements to the generative mechanism might not correspond to a simple stimulus feature, such as contour information, but may be more abstract, in the same way as a Fourier analysis of

![Diagram](image)

**(a)** Subjective pattern and contour. (a) Example of subjective contour, attributed to Schumann, 1904; taken from Hochberg, 1971. (b) Example of subjective pattern and contour (Growney, Millizer & Weisstein, 1971).

a stimulus is related in a more abstract way to the stimulus. The problem, then, may be one of definition of contour information as input to the relevant brain mechanisms. Generally, it
is not at all clear how contour information, however defined, is utilized in visual processing. A phenomenon which is promising as a useful tool in investigating this problem is metacontrast.

**Metacontrast and Edge Effects**

Metacontrast is the change in apparent brightness of a flashed target due to the simultaneous or subsequent flashing of a flanking stimulus called the mask; the mask does not overlap the target but the borders of the mask are near the borders of the target (e.g. Alpern, 1953, Weisstein, 1972; these are several reviews of masking studies: Raab, 1963; Kahneman, 1968; Weisstein, 1968; 1972; Lefton, 1972). Although masking has often been studied using threshold measures, the target also undergoes well-defined changes in apparent brightness (see Kahneman, 1968). These suprathreshold changes occur regularly with the changes in a variety of stimulus parameters, such as the temporal relationship between the offset of the target and the onset of the mask or the spatial separation between the target and mask. Because of these regularities it may be hypothesized that metacontrast may be a useful tool with which to investigate the mechanism(s) which determine(s) apparent brightness (see Weisstein, 1972). From this point of view, metacontrast with its temporal mapping of target-mask interaction, may be of particular usefulness in studying the first stages of pattern recognition. These early stages might include the effect of
edges in apparent brightness experience. In fact, various theorists have suggested that metacontrast data could be used to infer characteristics of how the visual system uses contour information or, in general, recognizes patterns (Werner, 1935; Hochberg, 1971; Weisstein, 1968; 1972).

Werner (1935) proposed that the disappearance of the target in a masking experiment was due to the assimilation of the neural code corresponding to the edges of the target by that of the contiguous masking stimulus. The assumption made by Werner was that the brightness of the target depended critically on the edge information of the target. In general, masking may not always be the result of contour interactions, but metacontrast with contiguous stimuli probably does involve an edge mechanism of some kind (Weisstein, 1972). Evidence supporting this observation may be found in a study in which the width of flanking rectangular masks was varied (from 1' to 98' of visual angle) in order to observe the change in apparent brightness of the target rectangle. Growney and Weisstein (1972) found that there was a critical area in which, increasing the width of the mask, produced a continuing decrement in apparent brightness of the target. The width of this critical area was the 10' radius of visual angle immediately adjacent to the edge of the target. The greatest amount of masking was contributed by the part of the mask within 2' to 4' of the target edge. This critical area was relatively the same regardless of target size or of kind of ocular input (monoptic or dichoptic). This
suggests: (1) that the change in brightness of the target depended only on the formation of the edges of the target, a formation hindered by the adjacent mask and (2) that the metacontrast interaction of target and mask was a nonperipheral effect (see also: Battersby & Wagman, 1962; Kahneman, 1968; Weisstein, 1968). Because pattern recognition probably involves cortical functioning, the involvement of metacontrast in nonperipheral processing suggests that metacontrast effects may be used to study the pattern recognition process (Kahneman, 1968; Weisstein, 1969; 1972).

Metacontrast is a useful technique in part because it is sensitive to a variety of temporal and spatial variables. The target and mask in a metacontrast experiment are transient stimuli and may be presented at various interstimulus intervals. The data from masking experiments, generally, are quite sensitive to changes in the energy relationship of target to mask. This relationship, defined in terms of the luminance and duration of the masking stimuli, has been used with patterned masks to sort out and isolate hypothesized processing stages in pattern recognition (Weisstein, 1968; 1972; Turvey, 1973). Metacontrast data are also sensitive to variations in the spatial location of target and mask. Studies in which the distance between target and mask are varied (e.g., Alpern, 1953; Weisstein & Growney, 1972), or in which the width of the mask is varied, keeping the target-mask separation constant (Growney & Weisstein, 1972), suggest that, at least, two spatial mechanisms
are involved in metaccontrast.

The hypothesis that metaccontrast involves contour activity seems tenable for clearly specified stimulus conditions (the conditions defining metaccontrast). With suitable stimulus input, therefore, metaccontrast data may yield information about the formation of edges in neural processing, about the interaction in neural processing of the representation of edges for one object or several objects, and, in general, about the effects of contour information during the early stages of visual processing which determine apparent brightness. In general, the function of edges in metaccontrast is not known. The edges of the target may be important in determining the amount of masking; the edges of the mask alone may be important or the interaction between the edges of the target and the edges of the mask together may be important in determining the amount of masking. The way in which the mask stimulus interrupts the pattern recognition process of the target stimulus is not known. This study is, in part, an attempt to assess directly the function of contour information in metaccontrast. By varying the luminance gradients at the edge of the masking stimuli, it will be possible to measure the relative contributions of both the mask and the target to the masking effect, and the extent to which the masking effect is a function of the contour information of the target and/or mask.
Hypotheses Regarding the Function of Edges in Metacontrast

The first hypothesis is that the amount of masking in a metacontrast experiment varies as a function of target edge gradient. There is evidence that the apparent brightness corresponding to an object is a function of the stimulus luminance at the edges of the object. The enhanced contour data reviewed above supports this observation. One interpretation of this view is Werner's (1935) hypothesis that the perceptibility of a stimulus depends on the formation in neural processing of the code for the edges of that stimulus. According to this hypothesis, metacontrast, the change in apparent brightness of the target due to the presence of the mask, occurs because the neural code of the mask interferes with the formation of the neural code for the edges of the target. In some way, as Werner hypothesized, the neural code for the edges of the target is assimilated by the neural code of the edges of the mask so that only the mask is seen. The neural code for the edges of the target is "added" to the neural code of the mask edges (see also, Frumkes & Sturr, 1968).

A different model of how the edges of the target may function in metacontrast is that the visual system may select edge information at some stage for special processing. Assume, for example, that some mechanism (such as a single cell) in the visual system functions as an edge detector (see, for example, Dodwell, 1971). Metacontrast could occur, according to this view, because the neural code for the mask nulls the
inhibitory flanks of the edge detector mechanism (see Growney & Weisstein, 1972). The neural code for the edges of the target is nulled, not assimilated, by the neural code for the edges of the mask.

In either case, with Werner's hypothesis or the edge detector hypothesis, it is expected that the edges of the target should be critical in determining the amount of masking which occurs in a metacontrast experiment. To find out how target edge information is used by the visual system, the characteristics of metacontrast will be studied as a function of target edge gradient. The luminance distributions of the target stimuli for this part of the experiment are shown in Figure 5. All three of the stimuli will be presented in rectangular windows of the same height and width. The luminance distribution across the width of the window, however, will vary as shown. The luminance distribution of the first target, sine (Figure 5a), is a half-cycle of a sine wave, truncated symmetrically at mid-trough. The edge gradient for Sine is very gradual; so presentation of the Sine target gives a minimum of edge information to the visual system for neural processing. The luminance distribution of the second target, Gate (Figure 5b), is uniform across the window, corresponding to a half-cycle of a square wave. The luminance distribution of the third target, Batman (Figure 5c), is a gate with enhanced contours. Batman, therefore, contributes the most edge information of the three stimuli to the visual system for neural processing.
Batman and Gate will be equated with respect to the amount of luminance to be presented in the target flash as averaged across the entire width of the stimulus. Both of these stimuli differ by at least a factor of two from the amount of luminance present in Sine. To control for amount of luminance, Sine will be increased proportionately in amplitude relative to the two other targets so that the three targets will be equivalent in average luminance across space. This Sine target will be called Sine A. It is unclear, however, whether or not this control is entirely suitable. An edge detector mechanism might receive stimulus information from only a small part of the visual field (see Growney & Weisstein, 1972). Averaging luminance across a fairly wide region in space, that is, across the entire width of the target, might be simply irrelevant to the mechanism mediating the masking effect. To study this possibility, Sine will also be presented with a luminance distribution equal in amplitude to the other stimuli. This Sine target will be called Sine R. While more masking would be expected for this target due to less target energy, the reduced masking for Sine R should be a constant proportion of the masking obtained for Sine A. This observation should be true, that is, if averaging luminance across space is a relevant control or if the particular target width used is sufficiently small with respect to the hypothesized edge detector mechanism.

If Werner's hypothesis is assumed to be correct, then the amount of masking obtained for the Sine target should be greatest
Fig. 5. Luminance distributions of the stimuli which differ primarily in edge gradient. Luminance distributions, L, across one dimension, x, in space for three stimuli: (a) Sine A, one-half cycle of a sinusoid, (b) Gate, a uniform distribution corresponding to one half-cycle of a square wave, (c) Batman, a Gate stimulus with enhanced edges. All three stimuli are equal in amount of luminance as measured from edge to edge.

because the neural code for the edges of Sine would be easily assimilated by the neural code for the mask edges. The edges of Batman are enhanced and should contribute the most edge information to neural processing. The amount of masking obtained for Batman should be the smallest of the four targets. In general, amount of masking for the four targets should be ordered from most masking to least masking according to edge gradient as follows: (1) Sine R, (2) Sine A, (3) Gate, (4) Batman. The edge detector hypothesis would predict the same ordering of amount of masking. Sine R, for example, would excite the edge detector less than the other three targets because of the more gradual slope of the luminance of Sine R with respect to space. The edge detector hypothesis predicts the same ordering of amounts of masking because the slopes of the edge gradient are directly related to the excitation of the edge detector. The amount of excitation of the edge detector is inversely related
to the predicted amount of masking or inhibition of the edge detector.

The first hypothesis dealt with the use of target edge information by the visual system. The second hypothesis is that the amount of masking in a metacontrast experiment varies as a function of mask edge gradient. Metacontrast may be an edge effect in the sense that the edge gradient of the mask is critical in determining the amount of masking which takes place. If masking were simply a function of mask luminance within 4' of the edge of the target, for example, then the order of greatest amount of masking of a given target from most effective to least effective mask should be: (1) Batman, (2) Gate, (3) Sine A, and (4) Sine R.

A previous study (Growney & Weisstein, 1972) measured the effectiveness of Gate masks of various widths upon the apparent brightness of a Gate target of 49' width. As described above, a weighting function lateral to the edge of the target was obtained which described this mask effectiveness. If masking is a function of weighted mask luminance near the edge of the target, then it could be expected that this weighting function should describe the differential masking of a given target which is obtained with masks which differ in edge luminance gradient. For example, the Batman mask should be more effective for a given target than the Gate mask. However, assuming the applicability of the weighting function, it would be expected that the difference in amount of masking obtained with the two different
masks would be of predictable magnitude as based on the weight-
ing function.

To find out how mask edge information is used by the visual system, the characteristics of metacontrast will be studied as a function of mask edge gradient. Four types of mask edge gradient will be used, corresponding in type to the four targets. To serve as masks, these stimuli will be used in pairs (both members with the same edge gradient) and will flank the target stimulus symmetrically.

A third hypothesis is that the amount of masking is also a function of the interaction of the neural codes corresponding to the contour information of the target and mask stimuli respectively. The effectiveness of a mask with a given edge gradient may depend upon the edge gradient of the target. Similarly, the maskability of the target may depend on the edge gradient of the mask.

One model which predicts an interaction would be the application of the views of Land and McCann (1971) to metacontrast. Assume that metacontrast is a transient effect of a system in which the apparent brightness of adjacent stimuli is determined by the product of the maximum/minimum ratios about the edge of each stimulus. The masking which is obtained with a given set of targets and masks with different edge luminance gradients might be proportional to the product of the maximum/minimum ratios of the target and mask stimuli. Land and McCann have demonstrated that their reflectance ratio hypothesis held
even for 10 msec flashes.

**Hypotheses Regarding the Temporal Characteristics of Metacontrast**

An intriguing feature of metacontrast is that the masking function is nonmonotonic. The mask has the effect of diminishing the apparent brightness of the target by the greatest amount when the mask is presented subsequent to the presentation of the target by 20-80 msec. Weisstein (1968) has shown that a sufficient model of metacontrast may consist of an excitatory component corresponding to the target, and an inhibitory component corresponding to the mask. Each component has a certain rise time to its maximum value. To account for the U-shaped metacontrast function in which the mask is most effective at a nonzero delay (backward masking), the inhibitory component is hypothesized to have a faster rise time. Maximum masking should occur when these two components peak at the same moment (see Figure 6).

There are at least two interpretations of the meaning of the inhibitory component and its relatively faster rise time. One interpretation (Weisstein, 1963) is that inhibitory processes with lateral connections develop at a faster rate than do excitatory processes in higher-order visual processing. The data are consistent with the hypothesis that metacontrast is a central event. However, no neurophysiological data could be found which support the hypothesis that differential development rates exist for inhibitory and excitatory processes in central portions of
Fig. 6. Hypothesized excitatory, E, and inhibitory, I, components illustrating Weisstein's (1968) two-factor theory of metacontrast. The ISI for peak masking is at $t = a$.

The visual pathway. In the periphery, the inhibitory process is at most as fast as the excitatory process (Weisstein, 1972). This suggests that the hypothesis of a faster inhibitory process in central processing is less probable.

A second interpretation of the fast rise time of the hypothetical inhibitory component which has been suggested by Weisstein is that instead of characterizing the properties of lateral interaction of inhibitory components, the fast rise time may reflect characteristics of a higher-order neural processing mechanism in which spatial features of the target and mask may be processed in different ways. For example, the mask may have to undergo only incomplete processing before it is able to interfere with the processing of the target. If the edges of stimuli are particularly important in processing, the neural code of the mask may be able to interfere with the formation of the neural code of the target before the neural code of the edges
of the mask are formed. In general, if processing time in the neural construction of patterns in perceptual processing is taken up by the formation of the neural code for edges, then differences in processing time for different edge gradients may be shown by shifts in the ISI for which peak masking occurs.

The neural code of the mask which interferes with the perceptibility of the target refers to an early stage of the pattern recognition process. The neural code of the mask could be interpreted in terms of Hebb's (1949) notion of primitive unity. Because the incompletely processed mask could interfere with the target, the inhibitory effects of the mask could be interpreted as developing at a faster rate.

Both hypotheses predict the same effects for targets and masks at zero separation for a neural edge mechanism. The lateral inhibition hypothesis predicts that for a given target, a mask with more luminance at its edge will produce a more rapid change in graded neural potentials resulting in a faster rise time for the inhibitory component. This increase in rise time predicts a shift of peak masking to longer ISIs (see Figure 7). This means that the Batman mask, for example, should have its maximum effect at a longer ISI than does the Gate mask. The incompletely processed mask hypothesis predicts that for a given target, the mask with a more completely formed edge will enter more rapidly into processing yielding a faster rise time. The Batman mask, therefore, should have its maximum effect at a longer ISI than should the Gate mask.
Fig. 7. Relation of neural rise time corresponding to the mask to the interstimulus interval (ISI) for which peak masking occurs in Weisstein's two-factor theory. The hypothesized excitatory component, E, corresponding to the target, is shown with the hypothesized inhibitory components, I, corresponding to the Gate mask (ISI of t = a) and to the Batman mask (ISI of t = b).

The same argument would predict that, given a constant mask, targets with sharper edge gradients would produce ISI shifts. The lateral inhibition model would predict that the graded neural potentials corresponding to a target with less edge luminance would rise more slowly. To obtain maximum masking, the mask would have to be shifted to longer ISIs (see Figure 8). The results for the Batman target, for example, averaged across ISIs, should show a temporal shift to a shorter ISI relative to the results for the Gate target. A similar argument would be made for the incompletely-processed-mask hypothesis.
Fig. 8. Relation of neural rise time corresponding to the target to the interstimulus interval (ISI) for which peak masking occurs in Weisstein's two-factor theory. The hypothesized inhibitory component, I, corresponding to the mask, is shown with the hypothesized excitatory components, E, corresponding to the Batman target (ISI of \( t = a \)) and to the Gate target (ISI of \( t = b \)).
A reasonable model of a pattern recognition mechanism is one in which the mechanism possesses a property-list system by which each object to be recognized is tested for the degree-of-presence of some characteristic which can efficiently define that object (e.g. Minsky, 1963). The characteristics of cells in the primate visual cortex can be interpreted as neurophysiological evidence of a property-list analysis in the visual pathway. A simple cortical cell, for example, is selectively sensitive to a slit of light in a particular orientation. The frequency of firing of single units, therefore, might serve to signal the presence of various properties (Dodwell, 1971; Weisstein, 1972). Such a property-list system is insufficient by itself to explain how a pattern is recognized (Minsky, 1963; 1968). The list of possible patterns is just too long to uniquely and efficiently define them all in terms of a limited set of properties. It seems likely that, in addition to the property-list system, the pattern recognition mechanism will need a visual syntax, that is, a list of rules for relating features to one another (for example, Guzman, 1969). Finally, some method of internal modelling is necessary, that is, the mechanism will have to generate hypotheses of how the pattern should look given a set of properties and a list of
rules for relating these properties. This internal model could then be compared with the input (see Minsky, 1963; 1968; Greene, 1964; and Weisstein, 1972). A possible example of the alternation of different hypotheses in an ambiguous situation is the Necker cube illusion (Gregory, 1966).

One of the major problems in relating artificial intelligence theory (for example, Minsky, 1963; 1968) to biological information processings is to understand how the information provided by single units in the property-list is integrated to serve as input to higher-order analyses, such as internal modelling. Any stimulus will generate a pattern of firing among many single units, exciting some units maximally, some mildly and others not at all. The problem is to describe the activity of a population of single units in an analytical manner.

There is evidence (Campbell & Robson, 1968) that the visual system performs a transformation on patterned stimuli such that the result of the transformation is related to the amplitudes of the Fourier components (spatial frequencies) of the stimuli. The information from single units may serve as input to this transformation. Pollen, Lee and Taylor (1971) also discuss how the cortex may perform a Fourier transformation on stimuli. This might mean that single units function throughout different stages of the pattern recognition process, fulfilling different requirements of the mechanism at different stages (Weisstein, Montalva & Ozog, 1972). On the other
hand, this interpretation might imply that the biological information processing mechanism is not fundamentally a property-list system at all, although some small set of features must be specified as input for higher-order transformations (Weisstein & Bisaha, 1972). In either case, the amplitudes of the Fourier components may be useful in constructing a model with which to characterize the activity of the population of single units which may influence visual experience.

Spatial Frequency Analysis and Detection

Fourier analysis techniques have been used to study the foveal spatial resolution of the human visual system. The goal of this kind of research has been to specify the transfer characteristics of the visual processing system and stages within the visual system. As is usually the case in a linear systems analysis, the transfer characteristics vary with the definition of the system input and output (Lathi, 1965). Whereas the input to the visual system is usually defined in terms of the luminance distribution corresponding to the visual stimulus, visual system output is variously defined in terms of the response measure. The threshold measure of detection of a sine wave as distinct from the background has been the most widely used method to determine the transfer characteristics of the visual system (e.g., De Palma & Lowry, 1962; Van Nes & Bouman, 1965; Patel, 1966; Campbell & Robson, 1968; Blakemore & Campbell, 1969). However, the transfer
characteristics of the visual system have also been obtained by using suprathreshold measures, such as brightness matching (Davidson, 1966; 1968), and indirectly, by comparing the spatial frequencies corresponding to the objective luminance distributions in Mach bands and the resulting subjective judgements of apparent brightness (Lowry & De Palma, 1961; see also Hay & Chester, 1970; 1972). In general, these functions show that the visual system is most sensitive to frequencies near 5 cycles per degree (c/d). The function decreases slightly for frequencies below 5 c/d, and falls off sharply for frequencies greater than 5 to 10 c/d.

This transfer function of the visual system is a composite of the transfer characteristics of the dioptric mechanism of the eye and the physiological properties of neural processing. The optical transfer characteristics have been determined independently (e.g., Westheimer & Campbell, 1962; Campbell & Green, 1965; Campbell & Gubisch, 1966). These characteristics are shown in Figure 6 of Chapter III. The eye sharply attenuates higher frequencies; the magnitude of this attenuation is a function of pupil size (Campbell & Gubisch, 1966). Patel (1966) has used Westheimer and Campbell's (1962) measure of the transfer characteristics of the eye to estimate the characteristics of the physiological properties of the visual system using linear systems techniques. The line spread function describing the neural part of the visual system is quite narrow and, therefore, does not
attenuate higher frequencies as sharply as does the optical mechanism (however, see Chapter III for a discussion of Patel’s estimate).

The predictive value of the transfer function for the visual system at threshold has been demonstrated for periodic stimuli (e.g., Campbell & Robson, 1963) and for aperiodic stimuli (e.g., Campbell, Carpenter & Levinson, 1969). Campbell and Robson (1968) showed that complex waveforms such as square waves, are indistinguishable from sine wave gratings at threshold until the harmonic components of the complex waves, such as the third harmonic for a square wave, reach their independent threshold. For aperiodic patterns, namely a single half-cycle sinusoid bar, a single full-cycle sinusoid bar and the boundary between an extended sinusoidal grating and a 50 percent gray surround, Campbell, Carpenter and Levinson (1969) showed that the differences in threshold for these three stimuli at different frequencies were in proportion to the expected amplitude (peak-to-trough) differences expected on the basis of a convolution of the Fourier inverse of the visual transfer function and the stimulus luminance distribution. Campbell, Carpenter and Levinson (1969) assumed that detection in the visual system was a function of a peak detector mechanism, that this peak detector was sensitive to the amplitude difference in the convolved stimulus. The agreement between the detection data and the predictions based on linear theory suggest that the visual system behaves in a
linear manner near threshold. Although the visual system is
generally nonlinear, due most likely to the logarithmic pro-
perties of the receptors (Mountcastle, 1968), the predictions
based on an assumption of linearity are valid for sufficiently
small excursions along the graphical axis describing luminance
input (cf., Nilsen, 1966).

Because the fundamental and third harmonic components
of a complex wave form, a square wave, seemed to function in-
dependently in the detection of the complex wave form, Camp-
bell and Robson suggested that independent channels selectively
sensitive to different spatial frequencies exist in the visual
nervous system. This suggestion is consistent with the find-
ings of Pantle and Sekuler (1968). They conducted a forward
masking experiment in which test gratings of 0.35, 1.05 and
3.50 cycles/degree (c/d) were masked by a series of adapta-
tion gratings. The peak of the threshold function for the
3.5 c/d grating occurred for masking gratings of higher
spatial frequency than did the peaks for the other two test
gratings. This result implied the existence of more than one
spatial frequency mechanism with differential tunings. Blake-
more and Campbell (1969) showed that an adapting sinusoidal
grating selectively depressed sensitivity to gratings of the
same frequency. In particular, they found that a square wave
grating raised the threshold for sine waves of both the
fundamental and the third harmonic frequencies, implying the
existence of multiple, independent spatial frequency mechanisms. Graham and Nachmias (1971) assumed that a single channel system would combine the fundamental and harmonics of the frequency components of a complex waveform to yield a larger peak-to-trough difference than would a system comprised of multiple channels which functioned independently. In this latter case, the independent channels would not combine their output; the maximum amplitude differences would, therefore, be smaller. Graham and Nachmias found that the multiple channels model predicted the characteristics of the detection data to a better extent than did the single channels model. Using a probability analysis in a similar experiment comparing the detection of simple and complex waveforms, Sachs, Nachmias and Robson (1971) also obtained results which were consistent with the hypothesis of independent channels. Although the number of these hypothesized channels is not determined, Campbell, Nachmias and Jukes (1970) observed that the ability of an observer to discriminate between two sinusoidal gratings was in proportion, primarily, to the ratio of the spatial frequencies over a wide range of frequencies (0 to 20 c/d). They concluded that there may be many frequency mechanisms with narrow bandwidth, slightly larger than one octave measured at half-amplitude (Blakemore & Campbell, 1969), and with center frequencies spaced at uniform intervals along a frequency continuum at intervals smaller than 1/20 octave.
However, there are at least two interpretations of the evidence supporting the existence of these independent channels (Sullivan, Georgeson & Oatley, 1972). One interpretation of this evidence is that there are a number of individual size-tuned mechanisms, that is, cells whose excitatory centers are optimally stimulated by bars of a certain width. Because all bars in a periodic grating are of the same size, the results obtained by Blakemore and Campbell could be due to the adaptation of all the cells with a particular-size receptive field (Thomas, Padilla & Rourke, 1969; Thomas & Kerr, 1969; Thomas, BAGRASH & Kerr, 1969; Thomas, 1970; Thomas & Kerr, 1971; BAGRASH, Kerr & Thomas; 1971; Blakemore, Nachmias, & Sutton, 1970). This hypothesis includes the assumption that the detectability of a stimulus is mediated by the individual cells or detectors for a given size. This kind of coding in neural processing can be called a feature coding; the feature being coded in this case is size.

A second interpretation of the evidence supporting the hypothesis of independent spatial channels is that the visual system itself does a Fourier analysis on visual stimuli (Poller, Lee & Taylor, 1971; Blakemore & Campbell, 1969; Julesz & Stromeyer, 1971; and Campbell & Robson, 1968). Assume that there is a spatial frequency mechanism tuned for each frequency so that the individual Fourier components themselves are available in neural processing as information about the
stimulus. Then, adaptation to a grating of a particular frequency would adapt out the neural units corresponding to that particular spatial frequency mechanism. This kind of coding can be called a frequency coding.

Both the frequency coding and the feature coding hypotheses predict the same results for periodic stimuli. Adaptation to a grating of a particular frequency, by hypothesis, would adapt out a size-tuned mechanism for one particular size and would adapt out the neural unit underlying the one particular spatial frequency mechanism or Fourier component. However, the two hypotheses predict different results if aperiodic stimuli are used. For example, a rectangle of luminance (a gate) would excite only spatially-localized size-tuned mechanisms according to a feature coding. In terms of a frequency-coding, the rectangle would excite a number of different neural units corresponding to many different spatial frequencies. An aperiodic stimulus, such as a rectangle or gate, is composed of an infinite number of spatial frequencies in the Fourier domain (e.g., Lathi, 1965). These selectively-sensitive frequency mechanisms would not be spatially-localized but would accept as input, stimuli anywhere in the visual field.

Studies which have used aperiodic stimuli have reported results that are consistent with the frequency coding hypothesis (Sullivan, Georgeson & Oatley, 1972; Weisstein & Bisaha, 1972). Sullivan, Georgeson and Oatley (1972)
demonstrated that, although adaptation to a grating of a specific frequency raises the threshold for gratings only within small limits about that frequency, adaptation to bars equal in width to one-half cycle of a particular frequency shows no such sharp tuning. This finding is consistent with the hypothesis that adaptation effects are related to frequency rather than to stimulus width. A similar suggestion can be made on the basis of the data of Weisstein and Bisaha (1972). Under suprathreshold conditions, Weisstein and Bisaha showed that the forward masking obtained with bars and gratings as stimuli was a function of adaptation duration. For short adaptation durations (0 to 150 msec.), a bar reduced the apparent contrast of the grating uniformly over the grating field. At an adaptation duration of 10 seconds, however, the masking effects of the bar were negligible. The uniformity with which the grating faded at short adaptation durations is consistent with predictions based on a frequency coding; the effects of the bar were not spatially localized.

**Spatial Frequency Analysis and Apparent Brightness**

Linear systems analysis has also been applied to the study of apparent brightness. The application is a difficult one because the visual system is certainly nonlinear (e.g., Cornsweet, 1970). The techniques of linear systems analysis accurately describe the characteristics of a system only if the system is linear or if a nonlinear system is operating
in a linear range (e.g., Milsum, 1966). This latter qualification probably describes the applicability of linear systems analysis to the characteristics of the visual system at threshold; the excursions of the luminance independent variable are kept small, close to threshold, and are therefore, approximately linear. The excursions of the luminance independent variable in suprathreshold studies, however, are usually much larger, on the order of several log units.

The major nonlinearity in the relationship between luminance and apparent brightness is a transformation which occurs early in the visual pathway. This transformation is roughly proportional to the logarithm of stimulus intensity and occurs somewhere between the early receptor potential and the late receptor potential in the retinal receptors (Cone, 1965; Brown, 1968). Lipetz (1968) has suggested that the transformation is more accurately described by the hyperbolic tangent of the logarithm of intensity; however, the logarithmic model is a useful first approximation (Cornsweet, 1970). If stimuli are corrected by the reciprocal of logarithmic intensity, visual processing subsequent to the logarithmic transformation may be linear (Mountcastle, 1968; Davidson, 1968). Whiteside and Davidson (1971) corrected their Mach band stimuli in this manner. Contrary to earlier studies of Mach bands (Ratliff, 1965), they found that the bright and dark Mach bands appeared symmetrical. This finding is consistent with the hypothesis that the logarithmic transformation
does occur early in the visual pathway and that subsequent visual processing may be linear.

Davidson (1963) obtained the modulation transfer function describing the transfer characteristics of the suprathreshold brightness system. He corrected his stimuli by a factor proportional to the reciprocal of the logarithm of the stimuli in order to neutralize the nonlinearity of the logarithmic transformation. He also used a method of analysis called perturbation analysis in order to obtain an estimate of visual system transfer characteristics for a small range of luminance in which the properties of the system would be approximately linear. This analysis had the effect of compensating for the large domain of luminance over which his stimuli varied (three log units). The resulting transfer function, which was obtained using a brightness matching response measure, was similar to functions describing the characteristics of the visual system at threshold in that the visual system is maximally sensitive to frequencies of 5 c/d. The suprathreshold transfer function, however, shows a larger low frequency attenuation than was obtained in some threshold studies (e.g., Blakemore & Campbell, 1969). However, other threshold measures of the transfer characteristics of the visual system also show significant low frequency attenuation (de Palma & Lowry, 1962; Campbell & Robson, 1963; Davidson, 1963). Davidson (1963) found no statistically significant
difference between the brightness matching and recognition threshold methods of determining the transfer characteristics of the visual system (see Hay & Chesters, 1970; 1972 for a discussion of differences in threshold and suprathreshold measures of visual transfer characteristics). Patel (1966), however, had shown that the low frequency attenuation in the visual transfer function may be a function of mean retinal illuminance. Patel did not obtain low frequency attenuation when mean retinal illuminance was 3 trolands and only slight attenuation at 10 trolands. Significant attenuation was obtained when mean retinal illuminance reached 1000 trolands (25 mL, using a 2 mm diameter pupil). The mean retinal illuminance used by Davidson was probably even larger than this because the apparent brightness of his adapting field was 750 mL. Blakemore and Campbell (1969), however, show no low frequency attenuation for mean spatial illuminance of 31 mL. The low frequency attenuation which is obtained at high levels of mean spatial illuminance is probably due to the effects of lateral inhibition (Patel, 1966; Cornsweet, 1970). These lateral inhibition effects apparently become insignificant at conditions of low luminance (Patel, 1966; see also Mueller, 1965).

Thomas (1968) studied the linearity of spatial integrations involving inhibitory interactions in suprathreshold visual processing, using a brightness matching technique. In
general, he found that sensitivity, measured by the reciprocal of the transmittance of the matching filter, was linearly related to the weighted sum of luminances in the visual field except for the lowest values of inducing luminance. This departure from linearity may represent a threshold of inhibition (Thomas, 1968) which is similar to that described above (Patel, 1966; Mueller, 1965). Another nonlinearity found by Thomas, however, is that the weighted elements in the visual field were not independent; the effect of a particular inducing segment depended upon what other segments were also illuminated. On the other hand, as Thomas points out, another test of linearity is whether or not different measures of the weighting function, which describes the transfer characteristics of the visual system with respect to space, yield substantially similar estimates from one type of experiment to another. On the basis of this criterion, the spatial visual system approximates a linear system. The weighting functions obtained by Bekesy (1960), Patel (1966) from the inverse Fourier transform of the visual transfer function, and Thomas (1966) are all markedly similar to the results obtained by Thomas (1968). Lateral inhibitory effects extend for a radius of approximately 10' of visual angle. Similar estimates of the weighting function characteristics were obtained in a metacontrast experiment by Growney and Weisstein (1972) and can be derived from the increment threshold data of Westheimer (1967). (A clear
exception to this similarity of measures is a metacontrast experiment in which small width stimuli served as targets and masks [Cox, Growney & Weisstein, in preparation]. Lateral inhibitory effects extended for over one degree of visual angle.) Hay and Chesters (1972) suggest that the nonlinearity of the visual system did not affect the broad characteristics of the signal transfer function which they obtained. In matching the brightness of small disks of different diameters to the brightness of a surrounding annulus at a large disk-annulus spatial separation, they found that the form of the brightness-disk diameter function was substantially unaltered with changes in contrast of the disk to the surround.

Bryngdahl (1966) in suprathreshold measurements of visual transfer characteristics using sinusoidal gratings, also showed that the general form of the characteristics did not change. These observations suggest that the effects of the suprathreshold neural processors are large in comparison to the smaller changes produced by visual system nonlinearity. At least, visual system nonlinearity may not seriously distort suprathreshold measures of visual transfer characteristics. Nonlinearity, however, can substantially alter predictions of brightness phenomena based on such measured transfer characteristics (Cornsweet, 1970) and must be treated carefully.

Even in a system with marked nonlinear characteristics, however, it is often useful to apply a linear systems approach
For limited excursions of the independent variable, the system may be approximately linear; to that extent a linear model may accurately describe characteristics of the system (such may be the case for the visual system at threshold). Depending on the biological system under study, the linear model describing the nonlinear system may be extended to include various nonlinear elements as long as the range of applicability describing these elements is specified. This approach has been applied with some success to the study of the retina-pupil system (Milsum, 1966). Relevant nonlinear elements for a model of the visual system, generally, would include brightness threshold and the logarithmic transformation. At the very least, a linear model is a useful first approximation to the unknown characteristics of a system (Milsum, 1966). Salient features of a system can be defined and the nature of the nonlinearities can be more accurately specified in this manner.

On the basis of the above assumptions, several studies of the suprathreshold visual system have been conducted to test the hypothesis that the visual system actually performs a Fourier analysis upon the visual input. The data obtained by Weisstein and Bisaha (1972) in which a bar masked a grating uniformly is consistent with this hypothesis. More striking support of the frequency coding hypothesis has been obtained in an adaptation experiment using a small black disk (10'
diameter) as the adaptation stimulus with a full field of concentric circles (bullseye) as the test pattern (Weisstein, 1973). The luminance distribution along any diameter through the full field would be described by a 15 c/d square-wave grating. These stimuli are the two-dimensional analog of the previous bar-gratings experiments with the added property of testing frequency and orientation effects simultaneously. The disk adaptation stimulus has a relatively flat frequency spectrum with a radially symmetric \((\sin X)/X\) structure. It proved to be a surprisingly effective mask, significantly so statistically, in comparison to the blank adaptation field, and masked the bullseye as effectively as a grating masks a bar of the same stripe width as the grating.

**The Function of a Frequency Coding in Visual Processing**

Correspondences between the psychophysical data and the predictions based on linear theory for threshold or near-threshold (as in Campbell & Robson, 1968) data have been based, generally, on one model of the use of frequency information in neural processing. It is assumed that the neural waveform corresponding to the stimulus is, in effect, convolved with a line spread function which is the inverse Fourier transform of the transfer function of the visual system. The threshold value for this stimulus is determined by the peak amplitude (peak-to-trough difference) in the result of this convolution (Campbell & Robson, 1968). Predictions based on this model
have been satisfactory for both periodic stimuli (Campbell & Robson, 1968; Blakemore & Campbell, 1969; Graham & Nachmias, 1971; and Sachs, Nachmias & Robson, 1971) and for aperiodic stimuli (Campbell, Carpenter & Levinson, 1969; Sullivan, Georgeson & Oatley, 1972).

While the assumption of a peak detector has yielded satisfactory results in the prediction of the threshold characteristics of periodic and aperiodic visual stimuli, the assumption does not meet the needs of a theory of visual masking. In order to predict masking effects, it is necessary to specify the manner in which the neural code of the masking stimulus interferes with the processing of the neural code of the target stimulus. If the visual system actually performs a Fourier analysis (Campbell & Robson, 1968), then the masking effect may be related to the interaction of the frequency spectra of the target and mask. It is assumed that the corresponding Fourier components are represented in the neural code corresponding to each stimulus. Armstrong and Sekuler (1972) assumed that the amount of masking of one pattern by another pattern would be related to the amount of commonality between the power spectra of the two patterns. They showed that the difference in power spectra corresponding to the target and various masks was chiefly the amplitude of the power spectra at the fundamental frequency. Using a forced-choice, identification measure in a forward masking experiment, Armstrong
and Sekuler found no proportional relationship between the differences in the amplitude of the power spectra at the fundamental frequency and the differences in amount of masking obtained with the different masks. Armstrong and Sekuler chose the amplitude of the power spectrum instead of the amplitude of the frequency spectrum as their measure of frequency effects. This is a reasonable choice in that the amplitude of the power spectrum describes the energy contributed by a particular frequency component. Other possible models, however, include measuring frequency effects in terms of the amplitude of the frequency spectrum, in terms of the total contribution of frequencies within a certain channel or group of channels (area beneath the frequency spectrum within limits defined by the bandwidth of the channels), or in terms of the total energy within a certain channel or group of channels (area beneath the power spectrum within limits defined by the bandwidth of the channels). On the assumption that information about the Fourier components corresponding to stimuli are in some way available for higher-order visual processing, this study will evaluate several such models.

Although Fourier analysis techniques have proved useful in predicting various visual phenomena, and although it is possible that the visual system could actually do a Fourier analysis (Campbell & Robson, 1968), it is not clear that the analysis which is performed in higher-order visual processing
is a Fourier one. Measures of the characteristics of the visual system as a whole include the transfer characteristics of various peripheral processing mechanisms, such as the optics of the eye and the logarithmic transformation early in visual processing. The resulting neural processing may not be like a Fourier analysis. On the other hand, there is some evidence with optical data-processing techniques that image recovery in nonbiological systems can be performed despite severe deformation of the Fourier amplitudes corresponding to the original image such as could occur in logarithmic or exponential transformations. The qualifications on this statement are that the phase relations must be kept relatively constant (e.g., Vander Lugt, 1968).

Metacontrast and a Spatial Frequency Transformation

Because aperiodic stimuli are the typical stimuli used in a metacontrast experiment, the spatial frequency hypothesis can be tested in a metacontrast experiment without confounding the frequency and feature coding hypotheses. It is not now known whether such a frequency coding has any import at the neural processing stage where the action of the mask on the target takes place. In particular, it is not known if the action of the mask on the target depends on the similarity of frequency coding of the mask and target.

Some data suggests that, in a metacontrast experiment, the action of the mask on the target depends on the similarity
of form and size between the target and mask (Mayzner & Tresselt, 1969; Uttal, 1970). Similarity of form between target and mask has been shown to be important in metacontrast by Uttal (1970) who reported that the greatest amount of masking at a constant spatial separation between target and mask was obtained for targets and masks similar in form. For example, greatest masking was obtained when rectangles masked rectangles of the same size; the same amount of masking was obtained when triangles masked triangles as when rectangles masked a rectangular target. These effects could not be expected if masking were a function, simply of contour proximity. The importance of form similarity is also indicated by the data of Mayzner and Tresselt (1969). Using a technique which they call sequential blanking, Mayzner and Tresselt found a decreasing masking as the squares in the second and fourth positions of a five square row were gradually changed to trapezoids. Because this effect was independent of the side changed, similarity of form, not adjacent contour, determined the amount of masking. Metacontrast, then, besides being a contour interaction, may also be an interaction between stimuli similar in form.

This second (form-specific) spatial mechanism may be characterized by a large spatial extent of lateral interaction. Although there is evidence for a spatial mechanism in metacontrast with negative lateral interaction effects of 10' of
visual angle in radius (see discussion above), there is also evidence of lateral interaction between target and mask in metacontrast which extends over spatial separations between target and mask of 1 to 3 degrees radius. These effects (large inhibitory fields) were obtained from studies in which the target and mask were similar in form (Alpern, 1953; Weisstein & Growney, 1969). It is possible that similarity of form between target and mask is necessary to obtain masking at large target-mask distances. Similarity of form may trigger the activity of a different spatial mechanism (but see the data of Barkoff and Sturr, 1971, where masking of a small disk target by overlapping disk masks was obtained with large masks).

If stimuli are coded in neural processing in terms of their spatial frequencies or the ratios of their spatial frequencies as suggested by Blakemore and Campbell (1969), then the interaction between stimuli similar in form may well be due to an interaction based on the similarity of spatial frequency coding of the stimuli. Interaction between stimuli similar in form may be a function of other properties than the spatial frequency coding of the stimuli in neural processing. However, the hypothesis that the visual system at some stage has the Fourier components of visual stimuli available as information about the stimuli is an interesting possibility worthy of test for several reasons. First, spatial frequency analysis has been useful in predicting the sensitivity of
observers to simple spatial distributions of luminance. Second, a frequency coding model could be extended readily to account for size constancy (Blakemore & Campbell, 1969) and as a basis for holographic-type memory (see Pribram, 1971). Third, spatial frequency analysis has been useful in predicting some effects in depth perception (Blakemore, 1970; and Fiorentini & Maffei, 1971). Taken together, these observations suggest that a Fourier analysis or some transformation like a Fourier analysis occurs in neural processing and may be a basic factor in a wide range of perceptual phenomena.

Contour Information and High Spatial Frequency

Another reason for studying spatial frequency information in metacontrast is that it may be possible to distinguish edge information from high spatial frequency information. Enhanced contour data suggest that edge information is critical in the apparent brightness of patterned stimuli. Yet, the visual system strongly attenuates high spatial frequencies (see, for example, Davidson, 1968; Campbell & Gubisch, 1966). This seems paradoxical because edge information and high spatial frequency information are equivalent in the visual stimulus.

Edge information and high spatial frequency information may also be equivalent in neural processing. Campbell, Howell, and Robson (1971) found that, if they left out the fundamental frequency for a square wave grating of 3 c/d or of lower fre-
quency under conditions of low contrast, observers would report seeing the square wave. This is an interesting result because the reported effect is a generation of an apparent brightness pattern (see also Chapter I) on the basis of frequency information. The frequency information that is important for the effect is probably the third harmonic; the third harmonic was important in other studies which contrasted the threshold characteristics of a sine wave and square wave of the same frequency (Campbell & Robson, 1968; Blakemore & Campbell, 1969). In an aperiodic visual stimulus, such as a gate, the third harmonic probably contributes to edge information (see Cornsweet, 1970).

It is not clear whether this influence of contour information represents a special application of the information contained in the high spatial frequency channels, a one-stage process, or whether there are actually two stages (at least) which influence apparent brightness. A two-stage mechanism, in terms of metacontrast, might consist of one stage in which edge information is critical, as amount of luminance near the edge of the target or mask, and a second, higher-order stage which involves interaction between neural units on the basis of similarity of frequency coding.

Hypotheses Regarding a Spatial Frequency Analysis

The basic hypothesis for this part of the study is that the amount of masking is a function of the similarity of the
spatial Fourier components of the target and mask (cf., Armstrong & Sekuler, 1972). To the extent that the frequency spectra of the target and mask are similar, the neural code corresponding to the target will be erased.

Specific spatial frequency hypotheses depend on the definition of spatial Fourier component similarity. One measure of similarity is a cross-correlation between the frequency transform of the target, $F_t(w)$, with the frequency transform of the mask, $F_m(w)$, such that

$$CC(w) = \int_{A}^{B} F_t(w) \times F_m(w-t) \, dw$$

where $t = 0$, and $A$ and $B$ depend on particular conditions (cf., Lathi, 1965). The domain of similarity which is defined by $A$ and $B$ might be the entire range of frequencies relevant to vision or might be confined to one or several channels of limited bandwidth within this range of frequencies.

A second measure of similarity is the ratio of target area to mask area beneath their respective frequency spectra within one or several channels. One hypothesis using this measure is that the amount of masking obtained with a particular set of stimuli is in proportion to the magnitude of this ratio such that a ratio of 1.0 of target frequency area to mask frequency area should correspond to the condition of most masking. Deviations from 1.0, either smaller or larger than 1.0, would be interpreted as measuring dissimilarity be-
tween the frequency spectra of the two stimuli and should correspond to conditions of less or little masking.

Another hypothesis using this second measure of similarity is that the amount of masking is a function of the dissimilarity between the frequency spectra of target and mask. Masking might occur to the extent that the frequency components of the mask spectrum are of greater magnitude within some channel or channels than are the frequency components of the target spectrum. The greater the Mask area/Target area frequency spectra ratio, then, the greater should be the amount of masking.

There are possible relations between the amount of masking and frequency spectra of the masking stimuli other than a comparison of the frequency spectra of the target and mask in terms of similarity. One such possibility is that amount of masking depends solely on the frequency components of the masking stimulus. Assume that the visual system at some stage samples the frequency spectrum of each stimulus at some frequency point or within some limited bandwidth about some particular frequency. This selectivity might occur, for example, within a frequency channel with a center frequency near 5 c/d, the frequency near which the visual system is most sensitive. If two stimuli are presented close together in time and space, the neural trace corresponding to the first stimulus may be erased depending on the magnitude of the frequency components within the selecting channel which
correspond to the second stimulus or mask. Amount of masking might then be a function of the magnitude of the Fourier component at some frequency within the frequency transform of the mask or the magnitude of the area beneath the frequency transform of the mask about the selecting frequency within the frequency limits or bandwidth of the channel.

To test these hypotheses, targets and masks will be constructed such that the frequency spectra of some stimuli will be identical while, for other stimuli, the frequency spectra will be quite dissimilar. The same stimuli will be used to test all forms of the spatial frequency hypothesis. The basic stimulus will be a Gate, a rectangle of the same height and width as was described in Figure 5b. However, the Gate stimulus will serve as a window for this part of the experiment. The stimulus luminance across the width of the Gate will be modulated sinusoidally at various frequencies, including zero frequency. An example of this stimulus arrangement is shown in Figure 9. In this way, the frequency spectrum of the mask can be manipulated and related to the amount of masking. The masks and targets will be equated for average luminance; the window width will be chosen such that gratings of different frequencies will be truncated by the window at the same part of a cycle (Kelly, 1971).

The stimulus arrangement described above makes use of the modulation theorem (e.g., Lathi, 1965). The multiplication of a spatial stimulus, \( f(x) \), by a sinusoidal signal of
frequency, $w_0$, translates the frequency spectrum of the original stimulus by $\pm w_0$. The frequency spectra of the target and mask, then, can be made to overlap to various extents by changing the modulating frequency of the Gate window for one or the other of the stimuli.

The stimulus configuration used to test the spatial frequency hypothesis also allows a test of the hypothesis that edge information is identical to high spatial frequency information in neural processing. The edge of the mask will be kept at a fixed spatial separation from the target. On different trials, the stimulus luminance of the mask will be modulated sinusoidally with different spatial frequencies. Changing the spatial frequency in the rectangular window in this manner will keep edge information fairly constant while high spatial frequency information is manipulated. Amount of masking can then be compared to different models of spatial frequency activity. In particular, models utilizing high spatial frequency (15 c/d) can be tested.

Edge information will be constant only with respect to spatial position, however, not with respect to luminance, because higher modulation frequencies will have smaller amounts of luminance near the edge of the mask. To control for this difference in luminance, differences in masking will be corrected for the differences expected simply on the basis of weighted luminance differences (see Model 3 below). If edge information is different from spatial frequency information
Fig. 9. Luminance distribution of a frequency-modulated gate stimulus. The horizontal luminance distribution, \( L \), with respect to space, \( x \), for a Gate target flanked by frequency-modulated Gate windows of 5 c/d.

In neural processing, masking of the target should be constant within the radius of 10' of visual angle about the edge of the target.

Models of Information Processing

In order to test the spatial frequency hypotheses about the relation of amount of masking to various measures of the similarity between the frequency spectra of the target and mask, it is necessary to specify any factors which might modify the frequency transform of the stimuli. These factors include the transfer characteristics of the equipment which presents the stimuli to the observer's eye, the transfer characteristics of the optics of the eye and of the logarithmic transform early in the visual pathway. These factors constitute a preprocessing of the stimulus input which will be categorized as chiefly peripheral to neural information processing. These factors will be discussed in detail in
Chapter III. Additional factors depend on the assumption of a particular model of visual information processing.

**Model 1.** Subsequent to peripheral processing, neural processing stages prior to the hypothesized comparison of frequency spectra may be adequately described by a Fourier analysis. In this case, there are no neural processing stages which modify the frequency characteristics of the stimuli. If the data are corrected for the transfer characteristics of the peripheral processing, then it will be possible to compare these data to the various hypotheses of frequency spectra similarity using the frequency spectra of the masking stimuli. The stages of Model 1 are, therefore, (1) peripheral processing, (2) Fourier analysis, (3) some use of the Fourier components to yield masking.

**Model 2.** Subsequent to peripheral processing, there may be lateral inhibition effects which can be described by a weighting function such as that of Campbell, Carpenter and Levinson (1969). For this model, the stages of information processing are (1) peripheral processing, (2) lateral inhibition characteristics described by a weighting function, (3) a Fourier analysis, and (4) some use of the Fourier components to yield masking. To compare the data to models of spatial frequency similarity based on the frequency transform of the masking stimuli, it is necessary to correct either the data or the frequency transform for the characteristics of stages (1) and (2).
Model 3. Assume that masking effects are due to the combined operation of two mechanisms. The neural code corresponding to the target may be attenuated by the operation of an edge mechanism, such as one described in the previous chapter. It will be assumed that the excitation of this edge mechanism is adequately described by the average of the weighting functions obtained for the three observers in Gromney and Weisstein (1972). By hypothesis, the second masking mechanism is one based on some use of the Fourier components of the masking stimuli. For this model, then, the stages of information processing are (1) peripheral processing, (2) a uniform attenuation (uniform with respect to space) of the neural code corresponding to the target stimulus which is proportional to the weighted mask luminance near the edge of the target, (3) a Fourier analysis, and (4) some use of the Fourier components to yield masking. In this case the data must be corrected for both the transfer characteristics of the peripheral processing and for factors describing the differential magnitudes of weighted mask luminance near the edge of each mask.

The purpose of listing these models of information processing is not as a prelude to a direct test of them by means of the data of this study. Rather, the models are listed to make explicit the assumptions underlying the hypotheses listed in the discussion above and to make specific tests of the spatial frequency hypotheses in terms of explicity-defined models of information processing.
CHAPTER III

METHOD

The stimuli for this study were slide negatives which were presented in a six-channel tachistoscope (Scientific Prototype, Model G). The tachistoscope was modified such that the distance from the bulbs to the plexiglass diffusing screen (8 cm.), and the distance from the diffusing screen to the slide negative (2 cm.), were equal for all of the channels. This modification, together with the replacement of the diffusing screens with plexiglass of known transmittance (40 percent), eliminated color differences between the different channels. The original equipment lenses in each channel were replaced by lenses of improved optical quality and known optical properties. They were 50 mm. in diameter with focal lengths, $f = 178$ mm. The effective angular magnification in each channel subsequent to the lens replacement was 2.16. The viewing field was 4.6 x 7.5 degrees of visual angle in size. The eyepiece of the tachistoscope was fitted with an artificial pupil of 2.00 mm. diameter.

The Stimuli

Combining the two parts of the experiment, there were a total of five different targets: Sine R, Sine A, Gate, Batman, and 5 c/d (cycles per degree) modulated Gate (all modulated Gates will hereafter be referred to in terms of their modulating frequency). There were also a total of eight different
masks: Sine R, Sine A, Gate, Batman, 2.5 c/d, 5 c/d, 10 c/d and 15 c/d. Each of these masks, however, was presented in pairs at six different spatial separations from the target: 1', 4', 12', 24', 48', and 84' of visual angle. Separation is measured laterally from the edge of the target to the edge of the mask. Therefore, eight times six or 48 masks were actually constructed. The analytical functions describing each of the targets are shown in Table 1. Each stimulus consists of a Gate window, 48' of visual angle in width, in which the luminance is modulated by the appropriate function. The constant, 83.5, which occurs in the equation describing the Batman stimulus was chosen such that the space average luminance of the Batman stimulus (total area beneath the Batman function) was equal to the space average luminance of the Gate stimulus (total area beneath the Gate function). The analytical functions describing the masks are shown in Table 2. The values for $x_0$ in degrees are equal to the width of a stimulus, 48' or 0.8 degrees, plus one separation. These values were used in all calculations with the exception of $x_0 = 0.315$ degrees which describes the separation of 1'. The analytical functions are actually out of phase for a Gate window at a separation of 1'. The actual stimuli were in phase with the window. To describe this case analytically, the 1' separation case was
Table 1

Analytical functions describing the luminance distributions of each of the five targets. The variable, $x$, is in degrees of visual angle.

<table>
<thead>
<tr>
<th>Target</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine R</td>
<td>$f(x) = [G_{0.8}(x)] \left[ 4.5 + 4.5 \cos(2\pi f x) \right]$ where $f = 1.25$ c/d</td>
</tr>
<tr>
<td>Sine A</td>
<td>$f(x) = [G_{0.8}(x)] \left[ 9.0 + 9.0 \cos(2\pi f x) \right]$ where $f = 1.25$ c/d</td>
</tr>
<tr>
<td>Batman</td>
<td>$f(x) = \int_{-0.4}^{+0.4} 9.0 G_{0.8}(x) \left[ \frac{83.5}{\pi} \left( \frac{A}{A^2 + (x-E)^2} + \frac{B}{B^2 + (x-E)^2} \right) \right]$ where $A = 0.0375656$ and $B = 0.0425921$</td>
</tr>
<tr>
<td>Gate</td>
<td>$f(x) = 9.0 G_{0.8}(x)$</td>
</tr>
<tr>
<td>5 c/d</td>
<td>$f(x) = [G_{0.8}(x)] \left[ 9.0 + 9.0 \cos(2\pi f x) \right]$ where $f = 5.0$ c/d</td>
</tr>
</tbody>
</table>

treated as zero separation such that $x_0 = 0.3$ degrees.

Construction of the Stimuli

In order to construct the stimuli, it was necessary to vary the density of the film in a regular manner to yield the desired luminance distribution. The photographic procedure which was adopted is based on a stimulus presentation technique devised by Davidson (1968). The basic strategy is that a transparency, such as the one shown in Figure 10, is swept in a horizontal direction across a frame of film. The luminance
Table 2

Analytical functions describing the luminance distributions of each of the 43 masks. The variable, $x$, is in degrees of visual angle. Each mask appeared for six separations of target and mask as determined by the value of $x_0$: 0.8, 0.87, 1.00, 1.20, 1.60, 2.20 degrees.

<table>
<thead>
<tr>
<th>Target</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine R</td>
<td>$f(x) = [Ga_{0.8}(x+x_0)][4.5 + 4.5 \cos(2\pi f[x+0.4])]$</td>
</tr>
<tr>
<td></td>
<td>$+[Ga_{0.8}(x-x_0)][4.5 + 4.5 \cos(2\pi f[x+0.4])]$</td>
</tr>
<tr>
<td></td>
<td>where $f = 1.25$ c/d.</td>
</tr>
<tr>
<td>Sine A</td>
<td>$f(x) = [Ga_{0.8}(x+x_0)][9.0 + 9.0 \cos(2\pi f[x+0.4])]$</td>
</tr>
<tr>
<td></td>
<td>$+[Ga_{0.8}(x-x_0)][9.0 + 9.0 \cos(2\pi f[x+0.4])]$</td>
</tr>
<tr>
<td></td>
<td>where $f = 1.25$ c/d.</td>
</tr>
<tr>
<td>Batman</td>
<td>$f(x) = \int_{x_0-0.4}^{x_0+0.4} 9.0 Ga_{0.8}(x+x_0) \left[ \frac{83.5}{\pi} \frac{A}{A^2+[x+x_0-E]^2}</td>
</tr>
</tbody>
</table><p>ight.$ |
|            | $\left. - \frac{B}{B^2+[x+x_0-E]^2]} \right] + \int_{x_0-0.4}^{x_0+0.4} 9.0 Ga_{0.8}(x-x_0) \left[ \frac{83.5}{\pi} \frac{A}{A^2+[x-x_0-E]^2}ight.$ |
|            | $\left. - \frac{B}{B^2+[x-x_0-E]^2]} \right]$ where $A = 0.0375656$ and $B = 0.042592$. |
| Gate       | $f(x) = 9.0 Ga_{0.8}(x + x_0) + 9.0 Ga_{0.8}(x - x_0)$.                  |
| Frequency  | Modulated Stimuli                                                       |
|            | $f(x) = [Ga_{0.8}(x + x_0)][9.0 + 9.0 \cos(2\pi f x)]$                |
|            | $+[Ga_{0.8}(x - x_0)][9.0 + 9.0 \cos(2\pi f x)]$                        |
|            | where $f = 2.5$ c/d, 5.0 c/d, 10.0 c/d and 15.0 c/d.                    |</p>
Fig. 10. The basic pattern (transparency), the image of which is swept horizontally across film. This method yields luminance gradients which, measured vertically, are proportional to curve 'a' on the pattern.

from the back-lighted transparency is integrated on the film, yielding horizontal bars of varying density, in proportion to the amplitude of the curve on the transparency. If the curve 'a' in the pattern transparency of Figure 10 is a sine wave, then the integrated luminance distributed on the stimulus slide negative will be sinusoidal; luminance will vary sinusoidally with distance along a vertical line drawn through the stimulus slide negative. The contrast of the stimulus gratings obtained in this manner can be controlled by changing the width of the opening in the transparency. Contrast was maximized by keeping the width of this opening small and close to the right-most excursion of curve 'a'.

The functions defining curve 'a' for each desired stimulus were sine waves generated and plotted using the Beckman-Ease analog computer at the University of Chicago with the exception of Gate and Batman. The Gate stimulus is simply a
window of the desired transmittance and will be described later. The function describing the Batman stimulus was constructed by convolving a Gate with the weighting function described by Campbell, Carpenter and Levinson (1969). The choice of this particular weighting function was, in part, arbitrary. The desired stimulus was to have enhanced edges; it was decided to provide an enhancement which had some relation to known visual processing characteristics.

One side of the functions was blackened (see Figure 10) and the graph was bound by rubber cement to a sheet of plate glass. The graphs were then photographed on Kodalith Ortho Type III film with standard Kodalith developer. This film is a high contrast film; it yields only complete transparency or opacity at any point under proper conditions. It is not a continuous tone film and was, therefore, ideal for constructing the transparency.

The apparatus for constructing the slide negative by sweeping the image of the pattern transparency across the film frame is shown in Figure 11. An approximation of a point source was obtained by putting a quartz-iodine bulb in an aluminum chassis box, directly behind a 0.8 mm. hole drilled in the front plate of the box. The ground glass portion of a standard microscope slide was fastened to the outside of the box in front of the hole to diffuse the projected light rays of the filament. The light from this source was collimated by a 50 mm. diameter achromat, corrected for spherical
aberration, with a focal length, \( f = 178 \text{ mm} \). This collimated beam passed through the transparency and was brought to a focus on the surface of the first surface reflector by a second lens. The second lens was an achromatic collimating lens of reasonably good quality which had been corrected for spherical aberration. It had a diameter of 51 mm. and a focal length, \( f = 392 \text{ mm} \). This fairly large focal length minimized lens distortion.

The first surface reflector was mounted on a Lafayette Pursuit Rotor. The motor was connected to a Powerstat variable voltage control so that the speed of rotation of the turntable could be controlled. The rotation speed of the turntable controlled the duration of the exposure of the image of the transparency on the film and, hence, the density of the obtained image. The collimated beam was reflected from the first surface reflector onto film in a Pentax Spotmatic camera from which the lens had been removed. The camera was mounted on the optical apparatus; procedures were followed to insure that the camera was properly oriented with respect to all three dimensions of space for all exposures. A one-to-one projection of transparency image to the film plane of the camera was achieved by equating the distance from the plane of the transparency to the second lens to the distance from the second lens to the film plane. This relationship could be finely adjusted by moving the transparency along the optical
bench until the image of a 15 c/d grating was brought to focus on the film plane using the camera viewfinder.

Each transparency was aligned with respect to the optical apparatus by projecting the image of the transparency onto a grid mounted on a wall at a distance of 186 cm. from the mirror. The grid had been aligned with respect to the optical apparatus. The transparency was therefore oriented with respect to the grid. The position of the transparency had to be adjusted slightly to bring the projected image to a focus. Good magnification of the transparency image was achieved in this way. Error due to transparency alignment was, therefore, minimized.

The speed of rotation of the turntable was monitored during each exposure. This was a necessary procedure because the rotation speed of the Rotor-Voltage Control system proved to be occasionally erratic. The actual speed which was finally selected was a joint function of the characteristics
of the developer. All exposures were made with a rotation speed of 4.2 rpm. The luminance of the collimated beam was measured with an S.E.I. photometer by placing a piece of plexiglass of known transmittance in the film plane. Luminance at the film plane was determined to be 40 ft.L. with the mirror stationary.

The film in the camera which yielded the stimulus slide negatives was Kodak High Contrast Copy film. This film was chosen because it gives good contrast (transparency or opacity) together with good continuous tones over a fairly small range of intensity. These characteristics are described by the slope, gamma, in the linear region of the Hurter-Driffield curve of photograph density versus luminance (energy per unit area) (Goodman, 1968). The gamma for High Contrast Copy film is 2 or 3, depending on the developer and development time. Unfortunately, a linear mapping of intensity onto film density is linear only when gamma is 1. The decision was made to accept some nonlinearity in order to maximize the contrast of the film (the contrast of the film was a basic requirement in order to obtain the metacontrast effect in the first place). This decision was reinforced by the limited luminance source available. In retrospect, a more suitable strategy would have been to use a lower contrast film (gamma = \( \frac{1}{2} \)) in conjunction with a more intense energy source for the stage 2 negative. These conditions would yield an overall
gamma of 1. Because desired values of gamma can be closely approximated (Goodman, 1968), this procedure seems feasible.

The greatest transparency which was obtained with the High Contrast Copy film was a transmission of 75 percent. The greatest opacity obtained with the film was 0.3 to 0.1 percent. This opacity was equivalent to complete light occlusion (observer's report). As will be discussed later, a 1.6 neutral density filter (2.5 percent transmission) completely occluded the stimulus flash (observer's report). The highest stimulus frequency generated was for the 15 c/d grating which had 4.5 lines/mm. This frequency is well within the cutoff frequency due to diffraction for Kodak High-Contrast Copy film of 60 lines/mm. (Goodman, 1968).

The film was developed with H&W Control Developer, one of the developers recommended for use with Kodak High Contrast Copy film. Unfortunately, the developer loses potency rapidly even when refrigerated. To control for this condition, the slide negatives were all developed simultaneously. Let these slide negatives which were obtained directly from the transparency be called "stage 1 negatives".

The conditions described above yielded close approximations to sinusoidal gratings. Only a few cycles of each frequency grating were needed to fill the Gate window as a stimulus. These cycles were selected from the center portion of the grating as a precaution against spherical aberration.
due to the lens. The gratings themselves were measured on an ARL Spectroline Scanner (courtesy of the Chemistry Department) with a slit width of 0.01 mm. This slit width was 4 percent of the width of the 15 c/d (cycles per degree of visual angle) grating, the highest frequency grating used in this experiment. The functions on the slide negatives were approximately sinusoidal as measured by the densitometer. A comparison of the theoretical sinusoidal values with the values of the densitometer readout were within +4 percent. Maximum error occurred in the regions of greatest transmission; the effect was to fill in the white stripes slightly. The transfer characteristics of the photographic procedure were almost a constant across frequency; the amplitude of the 15 c/d grating, where amplitude is equivalent to transmittance, was within 4 percent of the amplitude of the 2.5 c/d grating. Given a cutoff frequency of 60 lines/mm. for Kodak High-Contrast Copy film, an amplitude decrease of less than 7 percent would be expected for a grating of 4.5 lines/mm. or 15 c/d (see Figure 12) (Goodman, 1963). The peak of the sine waves was at 73 percent transmission; the minimum trough of the sine waves which could be obtained, keeping the generated functions sinusoidal, was at 16 percent transmission.

In order to present the stimuli against a background adaptation field, and in order to make the trough of the sine stimuli equal in luminance to this background field (to keep the frequency components corresponding to the stimuli
Fig. 12. Approximate transfer characteristics of the slide negative and of the tachistoscope lens. The characteristics of the slide negative, ---, based on a cutoff frequency of $f_0 = 60$ lines/mm. Those of the tachistoscope lens, ---, are based on a cutoff frequency of $f_0 = 359$ lines/mm. The position of the 15 c/d stimulus (4.5 lines/mm.) is shown, ---.
relatively simple and separable, the sine stimuli could not simply be placed in background windows of Kodalith film consisting of a clear window with a completely opaque surround. This requirement greatly complicated the stimulus construction procedure. The strategy adopted was to construct background windows of Kodak High Contrast Copy film which consisted of the clear window with a surround of the necessary transmittance to match the trough of the sine waves.

This procedure necessitated the printing of the sine waves (stage 1 negatives) onto Kodak High Contrast Copy film in each of the required positions for the 5 targets and 48 masks to fill the background windows. Using a Simmon Omega D-2V enlarger with a f = 90 mm. lens and an auxiliary focusing attachment to obtain one-to-one projection (contact printing introduced distortions similar to Airy patterns), these stage 1 negatives were used as templates. They were put in clear windows of Kodalith film which were identical in size and spatial separation to the desired Gate stimuli. These Kodalith windows will be called Kodalith templates I. The stage 1 negatives were shifted in phase within the Kodalith windows so that the resulting stage 2 negatives were in correct relation to the desired stimuli; for example, the density of the frequency stimuli (the stage 2 negatives) came to a peak at the lateral edges of the Gate stimuli. The same two stage 1 negatives of a particular stimulus were used to obtain the
the target and all six masks (six separations) for that stimulus. The projection was performed at an f-stop, $f = 32$, at exposures of 16, 17 and 18 seconds with a 2.0 neutral density filter between the projection beam and the stage 1 negative templates. These conditions were finally selected, based on the densitometer readout for the stage 2 negatives. The conditions provided a finer control of the density of the stage 2 negatives and yielded good copies of the stage 1 negative templates. The Batman stage 2 negatives were also obtained by following these procedures, using exposure durations on the enlarger of 6.5 through 8.0 seconds.

The next step in stimulus construction was the construction of the background windows. Kodalith templates II were first made consisting of black windows, which were identical in size and spatial separation to the desired stimuli, on clear surrounds. These templates II could not be obtained by contact printing the Kodalith templates I which were used with the stage 1 negatives, or by one-to-one projection of these templates I. Size changes in the stimuli occurred in a way which could not be controlled; the problem was that, besides the close tolerances demanded by the task, there was a triple constraint of Gate height and width and the separation between the two Gates comprising the masking stimulus. These could not be satisfied simultaneously. The desired Kodalith templates II were finally constructed by photographing white rectangles on a black background, with the separation between
the rectangles determined only after a great deal of trial and error. This procedure yielded Kodalith templates II of the desired exactitude.

These Kodalith templates II (black window on clear surround) were projected onto Kodak High Contrast Copy film under the same enlarger conditions used to obtain the stage 2 negatives (described above). The resulting background windows were clear windows, which were identical in size and spatial separation to the desired stimuli, with surrounds which matched the transmittance of the trough of the Sine stimuli, transmittance = 16 percent. These background windows were used for all stimuli with the exception of the Sine R stimuli.

The Gate stimuli were constructed by using the Kodalith templates I. The templates were simply projected onto Kodak High Contrast Copy film to obtain rectangles (Gates) of the desired transmittance, which were identical in size and spatial separation to the desired stimuli. The exposure durations on the enlarger were 3.0 through 4.0 seconds. The resulting negatives were the stage 2 negatives for the Gate stimuli. The transmittance of the Gate stimuli was set equal to the peak-to-trough mid point of the sine wave stimuli. This value of transmittance was equal to 45 percent.

All stimuli were to consist of a sandwich of the stage 2 negative and the corresponding background window of 16 percent transmission. A sample case, the 2.5 c/d mask, is diagrammed.
The transmission of the actual stimulus, the three-layered sandwich of the stage 2 negative, the background window and the two glass layers of the slide holder (standard Agfa 2" x 2" slides), was equal to the product of the transmittances at the corresponding points on the three layers. The peak of the 2.5 c/d sine wave, for example, was equal to $73\% \times 75\% \times 84\% = 46\%$. The trough of the sine wave is equal to $16\% \times 75\% \times 84\% = 10\%$. The background of the stimulus equals $16\% \times 75\% \times 84\% = 10\%$. Sample transmittance products for the other stimuli are presented in Table 3. These products were obtained in the same way as were the products in the above example.

The alignment of the stage 2 negative stimulus inside the background window, together with all measurements of
stimuli transmittances as a function of the transmittance of the layers comprising the final stimulus. Transmittance is in percent. The final value is the product of the layer transmittances.

<table>
<thead>
<tr>
<th></th>
<th>Stage 2 Negative</th>
<th>Background Window</th>
<th>Glass Holders</th>
<th>Final Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Sine A</td>
<td>73</td>
<td>75</td>
<td>84</td>
<td>46</td>
</tr>
<tr>
<td>Peak frequency-modulated stimuli</td>
<td>73</td>
<td>75</td>
<td>84</td>
<td>46</td>
</tr>
<tr>
<td>Peak Batman</td>
<td>73</td>
<td>75</td>
<td>84</td>
<td>46</td>
</tr>
<tr>
<td>Trough Sine A</td>
<td>17</td>
<td>75</td>
<td>84</td>
<td>10</td>
</tr>
<tr>
<td>Trough frequency-modulated stimuli</td>
<td>17</td>
<td>75</td>
<td>84</td>
<td>10</td>
</tr>
<tr>
<td>Gate</td>
<td>45</td>
<td>75</td>
<td>84</td>
<td>23</td>
</tr>
<tr>
<td>Batman Midpoint</td>
<td>41</td>
<td>75</td>
<td>84</td>
<td>26</td>
</tr>
<tr>
<td>Background (all stimuli except Sine R)</td>
<td>75</td>
<td>16</td>
<td>84</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Stage 2 Negative</th>
<th>Gate Window Filter</th>
<th>Background Window</th>
<th>Glass Holders</th>
<th>Final Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Sine R</td>
<td>73</td>
<td>62</td>
<td>75</td>
<td>84</td>
<td>23</td>
</tr>
<tr>
<td>Trough Sine R</td>
<td>27</td>
<td>62</td>
<td>75</td>
<td>84</td>
<td>10</td>
</tr>
<tr>
<td>Background Sine R</td>
<td>21</td>
<td>75</td>
<td>75</td>
<td>84</td>
<td>10</td>
</tr>
</tbody>
</table>

stimulus separation on the negatives, was accomplished using a microscope at a magnification of 20X. The reticle in the microscope gave effective gradations in terms of the stimulus of 0.002 inches at 20X. All separations between the two Gate windows comprising each mask were within 3 percent of the
stated values. The peak-to-peak measure of frequency for each sine wave was within 1 percent of the stated value of frequency.

The construction of the Sine R stimulus differed slightly from the construction of the other stimuli. The Sine R stimulus had to have an amplitude of 45 percent, equal to the Gate stimulus. In order to preserve the sinusoidal character of the stimulus, stage 2 negatives, consisting of sine waves with peaks of 73 percent transmission and troughs of 27 percent transmission were constructed. Exposure durations on the enlarger were 9.0 through 10.0 seconds. A series of Gate-like stimuli were then constructed which had clear surrounds but windows of 62 percent transmittance in the proper spatial positions. Exposure durations on the enlarger were from 1.0 to 2.0 seconds. The sandwich of these new stage 2 negatives with the proper Gate-like window of 62 percent transmittance yielded the Sine R stimulus with a peak of 46 percent and a trough of 17 percent transmittance. The actual Sine R stimuli, then, were constructed by sandwiching four layers: the stage 2 negative, the Gate-like filter (T = 62 percent), the background window and the 2 layers of the glass slide holder. Because the Gate-like filters had clear surrounds of 75 percent transmittance, however, a new series of background windows had to be constructed. These backgrounds had a transmittance of 21 percent; the negatives
were obtained with exposure durations of 3.0 through 9.5 seconds. As can be seen in Table 3, these values yielded the desired results.

A summary of the transmittances of the final stimuli, together with the actual luminance values corresponding to each stimulus, is shown in Table 4. The luminance in all channels of the tachistoscope was set to 50 ft.L. the maximum possible luminance. All luminance measurements in the tachistoscope were made with an S.E.I. photometer. Densitometer readings of the final stimuli showed that the error near the minima, 10 percent transmission, was rather small, about +1 percent. Errors near the peak of the stimuli, as for the sine waves or Gate, were no larger than +6 percent. The transmittance value at the peak of each stimulus was either at or within +6 percent of the tabled values. These values yield a luminance variation of about 3.0 ft.L. Variability of the same magnitude, +6 percent, also occurred on the slopes of the sine stimuli. The positive sign of the error indicates that the white stripes in the sinusoidal grating were slightly enhanced in luminance. An exception to this statement occurred with the Sine A stimuli where the sign of the error was negative, indicating less luminance on the slopes of the stimuli. At a point, 9' from the edge of the stimulus, the maximum error of -10 percent was reached. Two minutes from the edge the error was only -2 percent. At 13', the error dropped to -3 percent
Summary of the transmittance (in percent) and corresponding values of luminance (in footlamberts) for each of the stimuli. The channel source was set at 50 ft.L.

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Transmittance</th>
<th>Luminance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine A or Frequency-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulated Stimuli Peak</td>
<td>46</td>
<td>23</td>
</tr>
<tr>
<td>Trough</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Sine R Peak</td>
<td>28</td>
<td>14</td>
</tr>
<tr>
<td>Trough</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Gate</td>
<td>28</td>
<td>14</td>
</tr>
<tr>
<td>Batman Edge Peak</td>
<td>46</td>
<td>23</td>
</tr>
<tr>
<td>Mid-Stimulus</td>
<td>26</td>
<td>13</td>
</tr>
</tbody>
</table>

and was zero at a distance of 17' from the edge of the stimulus. In models of edge luminance which follow, therefore, estimates of edge luminance for the Sine A stimulus are overestimates. All sinusoidal stimuli, therefore, were only approximately sinusoidal. Although the magnitude of the error is not negligible, neither is it large (except for the edges of the Sine A stimulus). The stimuli should be close enough to the desired theoretical values to provide a useful approximation to frequency-modulated stimuli for a biological system. In the analyses that follow in Chapters IV and V, the theoretical functions will be used to describe the luminance distributions of the stimuli.

There was a third kind of error due, perhaps, to the shadow effects of dust particles in the image plane. Fluctuations of as much as 4 percent transmittance occurred in seeming
random fashion. They occurred on only occasional densitometer scans of the stimuli. Such irregularities were only observable on the surrounds of the stimuli where the transmittance was otherwise uniform. The effect was a uniform field with several tiny white spots. Although certainly undesirable, the overall effects of the irregularities were judged to be quite small.

All stimuli had thin dark lines of one-half minute of visual angle in size at the top and bottom of the rectangles. These dark lines were due to the overlap of the stage 2 negatives with the background of the background windows. This error was not considered significant on the assumption that metacontrast is primarily an effect of adjacent stimuli and that such error would not effect lateral processing. The lateral fit of the different layers for the final stimuli was good; certainly, no error was observable to the naked eye. The exception to this statement is that some overlap of layers occurred for the Sine R stimuli at the lateral edges of the windows. This overlap created a narrow dark line on either side of the window of, at most, one-half minute of visual angle in width. The Sine R stimuli were used with this error.

The Michelson contrast (Boynton, 1966) which was obtained with these stimuli varied. For the sinusoidal stimuli, using the luminance values of Table 4, the contrast was equal to
\[ \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}} + L_{\text{min}}} = \frac{23 - 5}{23 + 5} = 0.64. \]

For the Sine R and the Gate stimuli, the contrast was
\[ \frac{14 - 5}{14 + 5} = 0.48. \]

All stimuli were approximately equal in average luminance, measured across the width of the entire stimulus, with the exception of the Sine R stimuli which contain only one-half the space-average luminance of the other stimuli.

**Observers**

Two students were paid to serve as observers for this experiment. One observer WB, was naive to psychophysical experiments, generally, and to the purposes of this experiment in particular. The second observer, RS, was experienced with metacontrast experiments and with the metacontrast and spatial frequency literature. Both observers had 20/20 corrected vision. Observer, WB, wore glasses which added approximately 1 cm to his viewing distance in the tachistoscope. This increased distance actually corrected magnification error in the tachistoscope, such that the modulation frequencies were correct to within 0.01 cycles/degree. Observer 2 wore contact lenses. The underestimation of the magnification in the tachistoscope meant that the modulation frequencies were slightly less than the stated values for O2. The largest error was for the 15 c/d mask which was actually 14.75 c/d for O2. The 10 c/d grating
was actually 9.38 c/d. All other error was less than 0.1 c/d.

**Procedure**

The stimuli were presented monoptically, to the right eye of the observer. The head of the observer was stabilized by means of a forehead and chin rest. A fixation point of 1' diameter appeared on an otherwise uniform adaptation field of 10 percent transmittance. This fixation point was one degree to the right, and 50' up from the center of the target. The adaptation field was continuously exposed except during the presentation of either the target or mask fields. Observers reported that, during the stimulus presentation sequence of adaptation field-target field-adaptation field (for the ISI duration) - mask field - adaptation field, there was no observable evidence of the onset or offset of the different fields other than the presence or absence of the stimuli.

In outline, all stimuli were rectangular windows, 48' of visual angle in width by 96' of visual angle in height. The exposure durations of both the target and mask stimuli was 16 msec. All luminance flashes were monitored for amplitude and duration by means of phototubes placed in each channel of the tachistoscope. The phototube output was displayed on an oscilloscope. The calibration of luminance in terms of phototube output was checked twice weekly.

The observer adapted to the luminance of the adaptation field for at least five minutes prior to each experimental
session. Each observer participated in two one and one-half hour sessions daily with a minimal rest period of one-half hour between sessions. The observer was free to rest at any point during the session or to take a more prolonged break depending on the onset of fatigue. These extra periods of rest were seldom taken. The observer controlled the onset of the stimulus sequence or trial. There was at least a delay of 3 sec. between trials.

The four stimuli differing primarily in edge gradient (the edge gradient stimuli) were Sine R, Sine A, Gate and Batman. Each of these stimuli were used as target and, in pairs, as masks. This defines 4 x 4 or 16 conditions. For the stimuli used to study spatial frequency effects (frequency stimuli), there were the two targets, Gate and 5 c/d, with five different masks, Gate, 2.5 c/d, 5 c/d, 10 c/d, and 15 c/d. This defines an additional 4 + 5 = 9 conditions; the Gate target, Gate mask condition was included above. Each one of these 16 + 9 = 25 conditions was presented at 6 different spatial separations of target and mask: 1', 4', 12', 24', 48', and 84' of visual angle, for a total of 25 x 6 = 150 conditions. Each of these 150 conditions was presented at 11 different temporal delays (ISIs) between target and mask: 0, 20, 40, 60, 80, 100, 120, 140, 130, 220 and 300 msec. These ISIs (inter-stimulus intervals) are measured from the offset of the target to the onset of the mask. One complete replication of the experiment for one observer, therefore, consisted of 150 x 11 =
1650 trials. There were a total of 3 replications for each observer.

Within one replication, the 150 conditions of target-mask-separation combinations were randomized. Each condition was presented at the 11 ISIs which were also in random order. One experimental session consisted of 25 target-mask-separation conditions for a total of 275 responses.

Each observer completed two replications of the experiment as practice sessions prior to the eight experimental replications. These practice sessions were identical to the experimental sessions with the exception that each condition was presented at additional ISIs of \(-100, -60, -40, -20, 0^-\) (where \(0^-\) means the onset of the target followed the offset of the mask with no delay). These ISIs define the condition of forward masking, measured from the offset of the mask to the onset of the target. No forward masking was obtained at these delays with any of the stimuli combinations. They were therefore omitted from the experiment proper.

**Response Measure**

To quantify the apparent brightness of the target stimulus, the Stevens' magnitude estimation procedure was used (Stevens, 1957). A modulus of 10 was assigned to the target flash, presented by itself. In relation to the modulus of 10, the observer was instructed to give a number which described the apparent brightness of the target on each trial. The
observer was instructed to assign a zero to the apparent brightness of the target when the target could not be seen, even though the observer could distinguish trials in which the target had been flashed but occluded from trials in which the target was not flashed at all (cf., Fehrer & Raab, 1962). For the 5 c/d target, the observers were asked to give two ratings on each trial: one number describing the apparent brightness of the target in comparison to the modulus of 10, and a second number describing the contrast of the 5 c/d target, where a 10 was assigned to the 5 c/d target flashed by itself and a zero contrast was assigned to the condition where no white or black bars could be distinguished, such as in the flash of a Gate target by itself. The presentation of this modulus was under the control of the observer; he was free to use it at any time during the experimental session. Typically, the variance of the observer's responses diminishes to a steady level with 5 to 10 hours of practice, using the magnitude estimation procedure. However, once this steady level is reached, the variance of the measure changes as a function of ISI. Variance is at a peak for the ISI yielding the greatest masking (see Chapters IV and V). There is very little variance in the ratings of the observer for very small ISIs (as 0 or 20 msec.) or for very large ISIs (as 140 msec. and above).
The Correspondence of Magnitude Estimations to Values of Luminance

Each observer was asked to rate the apparent brightness of flashes of a stimulus identical in size to the Gate target. This test stimulus was constructed using opaque strips of Kodalith film; a rectangular opening the size of the Gate target was constructed. When the channel containing this stimulus was triggered, the observer saw a flash identical in size and spatial position to the Gate target against a black background. The observer first adapted to the luminance of the adaptation field with the fixation point. The regular Gate target of the experiment was used as the modulus of 10. One of a series of neutral density filters was then positioned in front of the test stimulus. There were 15 such gelatin filters (Kodak Wratten Neutral Density Filters) with 11 filters with values of 0.1 to 1.1 in steps of 0.1, and four filters with values of 1.4, 1.6, 1.8 and 2.0. For both observers, the 1.6 filter completely occluded the target flash. The series of 15 neutral density filters with the test stimulus flash was presented to the observer in random order. This series was replicated 4 times at the end of a particular experimental session. This procedure was repeated three times during the course of the experiment, after 16, 32 and all 48 sessions, for a total of 12 replications. The geometric mean of the magnitude estimations for each neutral density filter condition
is plotted as a function of luminance in Figure 14. According to Stevens' Power Law, this graph on log-log coordinates should be a straight line. The data for each subject are, in fact, best fit by two straight lines. The resulting power equations for each observer are shown in Table 5. The values for these equations were obtained by a graphical approximation to Figure 14.

Table 5
Equations describing the relationship of magnitude estimations, \( B \), to luminance, \( L \), for each observer. The domain of values of \( L \) is in footlamberts.

<table>
<thead>
<tr>
<th>Observer 1</th>
<th>Observer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B = 0.240 , L^{1.363} ) 2 &lt; ( L ) &lt; 15</td>
<td>( B = 0.212 , L^{1.333} ) 2 &lt; ( L ) &lt; 18</td>
</tr>
<tr>
<td>( B = 4.00 , L^{0.318} ) 15 &lt; ( L ) &lt; 50</td>
<td>( B = 3.12 , L^{0.403} ) 18 &lt; ( L ) &lt; 50</td>
</tr>
</tbody>
</table>

The exponents which describe the data of each observer must be considered a function of the particular conditions of this experiment. The flashes of the test stimulus were quite short, 16 msec., rather small, 48' x 96' of visual angle, and appeared against a black surround. Nonetheless, some comparisons can be made to the results of other magnitude estimation studies. Each observer gave a rating of zero to a target flash of 1.25 ft.\( L \). The slope of the function for stimulus values smaller than 2 ft.\( L \) (not shown in Figure 14) is very steep. This steep slope of the graphs for stimulus flashes of 2 ft.\( L \) or less is typical of power equation results for
weaker, less intense, stimuli (Engen, 1971). There is quite a rapid increase in sensitivity for increasing stimulus energy at these low levels of stimulus energy. On the other hand, the very small slope, for stimulus flashes of 15 to 13 ft.L. or more, 0.318 for observer 1 and 0.4 for observer 2, are representative of power law equations which are obtained for larger values of stimulus luminance. Stevens' (1966) pointed out that flashes of the order of 1 sec. have an exponent equal to 0.33. Shorter flashes of luminance might be expected to correspond to slightly larger exponents, such as 0.4 or 0.5. This was true for the data of observer 2; it was not true for the data of observer 1.

It is not clear why the change in slope between the two uppermost lines for each observer in Figure 14 should take place in the luminance range of 12 to 14 ft.L. On the one hand, these values may define the large values of luminance for the conditions of this experiment, similar to the range of large values of luminance in other experiments (as described in Stevens, 1966). On the other hand, the actual value of the Gate modulus was 15 ft.L. which is near the intersection of the two uppermost lines for each observer. Perhaps, the modulus adjusts the relative criterion of the observer in this regard. The exponents for the two observers in the middle range of stimulus intensity, from 2 ft.L. to 15 or 18 ft.L. were quite similar: 1.36 for observer 1 and 1.33 for observer 2. Most
ratings of the target stimulus during the experiment were made within this range.

The Transfer Characteristics of Peripheral Visual Processing Systems

In order to specify what spatial characteristics of the stimuli are available in the neural code for higher-order
processing, it is necessary to know how the spatial characteristics have been modified by peripheral visual information processing systems. In the context of this experiment, these systems include the slide negative, the tachistoscope, the optics of the eye and the logarithmic transform early in the visual pathway.

Assuming that the most effective range of visual frequencies in suprathreshold vision is centered about 5 c/d and does not extend much higher than 25 c/d, the stimuli were modified only slightly by the transfer characteristics of the slide negative or the lens in the tachistoscope. The transfer characteristics of the slide negative have been described above.

The major processing component in the tachistoscope was a lens, identical in properties for all three channels, with a diameter of 50 mm. and a focal length, f = 178 mm. This was a lens of fairly good quality. It is assumed that the processing effects of the first surface mirror and prism were small compared to the effects of the lens. The optical transfer function for this lens was approximated in the following manner. The cutoff frequency, \( f_0 \), for a diffraction-limited system with a spatially incoherent illumination source with a square exit pupil is given by (Goodman, 1963)

\[
f_0 = \frac{L}{vD'}
\]

where \( L \) is the width of the square aperture, \( v \) is the wave
length of the illumination, and $D'$ is the distance from the aperture to the object (slide negative). The aperture in front of the lens in the tachistoscope was actually rectangular. Because all analyses involving spatial frequency are being confined to the one, horizontal dimension, $L$ was set equal to the width of the aperture, $L = 3.0$ cm. The value for $v$ was set equal to the middle frequency for the visible range of the electromagnetic spectrum, $v = 5.5 \times 10^{-5}$ cm. The distance from the aperture to the slide negative was $D' = 15.2$ cm. Substituting these values in the above expression gives $f_0 = 359$ lines/mm. This value of cutoff frequency was used to approximate the optical transfer function of the lens; this function is shown in Figure 15. The decrease in amplitude for a stimulus of 15 c/d (4.5 lines/mm.) is no more than 2 percent. The combined transfer characteristic of the film and of the tachistoscope lens for a 15 c/d grating is, therefore, the product, 94 percent times 98 percent = 92 percent. This 8 percent decrease for a frequency of 15 c/d (with proportional decreases for other frequencies) is a small decrease compared to the modulation effects of other systems, such as the optics of the eye. This estimate is a conservative one in that the slope of the transfer characteristic for film or lenses is less negative near frequencies of 0 lines/mm.

The most important modulation of the spatial frequencies corresponding to the stimuli occurs in the optics of the eye. The line spread function which describes these modulation
Fig. 15. Transfer characteristics of the optics of the eye. These characteristics are based on a graphical approximation to the published data of Campbell and Gubisch (1966) for a 2.4 mm. pupil.

properties in the spatial domain is a function of pupil size. Westheimer and Campbell (1962) estimated the line spread function for a 3 mm. artificial pupil to be given by

\[ f(x) = e^{-0.7|x|} \]

where \( x \) is expressed in minutes of visual angle. Using a different technique, Campbell and Gubisch (1966) obtained narrower estimates of the optical linespread function. The narrowest function they obtained was for a 2.4 mm. artificial pupil. A graphical approximation was made to obtain a conservative estimate of the linespread function for this 2.4 mm. pupil as the closest available description of eye optic characteristics for the 2 mm. pupil used in this study. The function is given by
\[ f(x) = e^{-60|x|} \]

where \( x \) is expressed in degrees. Use of the appropriate Fourier transform yields the curve of normalized Gain versus frequency which is shown in Figure 15. Gain decreases rapidly with increasing frequency. The amplitude of the 15 c/d component, for example, is only 29 percent of the amplitude of the 0 c/d component.

In order to correct the stimulus gratings for the transfer characteristics of the optics of the eye, it would have been necessary to increase the amplitude of the 15 c/d grating, for example, by a factor of almost \( 1/0.29 \) relative to the amplitude of the 2.5 c/d grating. The difficulty with such a correction was that the channel sources of the tachistoscope were limited to a reliable output of 50 ft.L. maximum. This means that the amplitude of the 15 c/d grating would have been set at 75 percent of 50 ft.L. and the amplitude of all other gratings proportionately attenuated. The amplitude of the 2.5 c/d grating, for example, would have to have been reduced to 0.308 of the amplitude of the 15 c/d grating. This reduction would have yielded almost negligible contrast, given the 50 ft.L. source available. It was chiefly for this reason that the strategy to correct the stimuli was abandoned.

However, there is at least one other difficulty with the strategy of correcting the stimuli for the transfer characteristics of the eye optics. While such a strategy is, in
principle, feasible for gratings, the strategy is not as straight forward for aperiodic stimuli. Sinusoidal gratings have only one frequency component; it is practical to amplify or attenuate the amplitude of that component with respect to the amplitude of the optical transfer function at that particular frequency. However, an aperiodic stimulus, such as a 15 c/d modulated Gate, has a continuous frequency spectrum. The luminance function which was generated by the analog computer to be used as the transparency template would have to have been the convolution of the sinusoidally modulated Gate and the reciprocal of the optical line spread function. It would have been insufficient to have modified only the sinusoidal grating by the transfer characteristics of the eye optics.

Within the context of testing the particular spatial frequency models described in Chapter II, the failure to correct the stimuli for the transfer characteristics of the slide negatives or the optics of the eye was not necessarily critical. A comparison of the masking effects for masks of different modulating frequencies which assumes the existence of independent channels in visual processing substantially moderates the need to take such factors into account. This topic is developed more fully in Chapter V.

The third peripheral visual processing system is a logarithmic transformation. Studies of the electroretinogram
have suggested that there is a logarithmic transformation early in the visual pathway, perhaps as early as the late receptor potential (Cone, 1965; Brown, 1968). Whiteside and Davidson (1971) corrected their stimuli by the reciprocal of a logarithmic transformation. They found that the bright and dark Mach bands appeared symmetrical. This finding is consistent with the hypothesis that the logarithmic transformation does in fact occur early in the visual pathway. Subsequent processing in the visual pathway may be linear (Mountcastle, 1963; Cornsweet, 1970). In order to test the hypotheses of this study in terms of specific models of information processing, the assumption has been made that the logarithmic transformation is peripheral to the activity of the neural mechanisms which mediate masking. In this sense, the logarithmic transformation may be considered peripheral and is so treated in this paper.

A logarithmic transformation would effect the amplitude of the Gate stimulus relative to the amplitude of the frequency-modulated Gate stimuli. For example, the 14 ft.L. Gate was one-half the amplitude of the 23 ft.L. peaks of the Sine waves relative to the 5 ft.L. background.

\[ \frac{14 - 5}{23 - 5} = \frac{9}{18} = 0.5 \]

Because of the logarithmic transformation, however, the amplitude of the Gate stimulus relative to the peak of the Sine waves was actually 0.625. Using natural logarithms which correspond
to the numbers above,

\[
\frac{2.639 - 1.609}{3.135 - 1.609} = \frac{1.030}{1.525} = 0.625
\]

The amplitude of the Gate stimulus relative to the 5 ft.L. background would have to have been decreased by 37 percent to yield a ratio of Gate amplitude/peak Sine wave of 0.5. This would have yielded a Gate target of 10.7 ft.L. As with the correction for the optics of the eye, it was decided that the diminution of contrast would be so great as to preclude masking effects of sufficient magnitude to be able to test the hypotheses. The average luminance of the Gate stimulus was, therefore, slightly more than the average luminance of the frequency-modulated Gates.

The logarithmic transformation also changes the spatial frequency spectra of the stimuli. In order to assess the extent of these changes, a comparison was made of the frequency spectra corresponding to the luminance of the stimuli and to the logarithm of the luminance of the stimuli. The frequency spectra were obtained and plotted using a Fast Fourier Analysis Program titled, "A Radix-Eight Fast Fourier Transform Subroutine for Real-Valued Series", courtesy of Bell Telephone Laboratories. The change in frequency magnitudes because of the logarithmic transformation was surprisingly little, especially at low frequencies. The relative amplitudes for corresponding points within each frequency spectra, for example, comparing the frequency spectrum of the 5 c/d mask to the
frequency spectrum of the logarithm of the 5 c/d mask, were either identical or differed by only a few percent. The most significant changes in frequency magnitudes introduced by the logarithmic transformation were at twice the modulating frequency for the frequency-modulated stimuli. In the spectrum corresponding to the logarithm of the 5 c/d mask, for example, there was a drop in amplitude around 9 c/d, followed by an enhancement at 10 c/d, followed by reduced amplitude for all higher frequencies. For the 10 c/d and 15 c/d masks, these changes occurred about frequencies of 20 c/d and 30 c/d, respectively. The main effects of these changes are the following. Because of the decrease in amplitude at higher frequencies above the modulating frequency for the frequency spectra corresponding to the logarithm of the stimuli, the computed areas for the 2.5 c/d mask at centering frequencies of 10 c/d and 15 c/d, and for the 5 c/d mask at a centering frequency of 15 c/d are inflated, relative to the areas computed for the other masks (see Chapter V). As will be seen, however, these differences are small compared to the disparities between the predictions of the various models of spatial frequency and the metacontrast data. In general, although the effects of the logarithmic transformation are certainly measurable (e.g., the changes in the Gate stimulus), the luminance variations among the stimuli are only over a luminance range of about one log unit. Departures from linearity over this small range are probably not large (cf., Cornsweet, 1970).
Comparison of the Apparent Brightness of the Stimuli

The apparent brightness of each kind of mask was compared to the apparent brightness of each of the other masks in order to obtain some measure of the magnitude of the differential effects of nonmetacontrast mechanisms using each of the stimuli. To obtain this comparison, the masks giving a target-mask separation of 48' were used to represent each kind of stimulus. The two Gate windows comprising this mask were three times 48', or 144' of visual angle apart, measuring the innermost edges of the two windows. It was assumed that the spatial summation effects of the flashes of the two Gate windows when the mask alone was triggered were independent of each other.

Spatial summation effects usually occur over a much smaller range, such as 20' of visual angle, as described by Ricco's law (e.g., Graham, 1965). Although partial summation influences threshold measures over a much larger area, such as 10 degrees (e.g., Riggs, 1971), suprathreshold measures of spatial summation show a smaller domain of effect of about 15' (Thomas, 1968). The apparent brightness of the right Gate window of this mask for each kind of stimulus was rated using the method of Magnitude estimation. The Gate mask was assigned a modulus of 10 and was used as a standard. A fixation point was constructed which had the same spatial relationship to the right window of the mask as existed between the fixation point and target stimulus in the experiment proper; it was 60' to the right of,
and 50' above, the center of the right window. The seven stimuli, Sine R, Sine A, Batman, 2.5 c/d, 5 c/d, 10 c/d and 15 c/d masks were presented in random order to the observer. Five replications of this experiment were performed on two occasions, at the middle and end of the large experiment, for a total of 10 replications. Unfortunately, the Gate mask was not included in the ratings. It is assumed that the mean rating for the Gate mask would have been 10.0.

The geometric means of the magnitude estimations for each of the stimuli for each observer are shown in Table 6.

Table 6

<table>
<thead>
<tr>
<th>Stimuli</th>
<th>Observer 1</th>
<th>Observer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine R</td>
<td>3.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Sine A</td>
<td>10.7</td>
<td>11.4</td>
</tr>
<tr>
<td>Batman</td>
<td>10.1</td>
<td>9.9</td>
</tr>
<tr>
<td>2.5</td>
<td>9.8</td>
<td>10.7</td>
</tr>
<tr>
<td>5</td>
<td>10.2</td>
<td>10.9</td>
</tr>
<tr>
<td>10</td>
<td>9.2</td>
<td>10.1</td>
</tr>
<tr>
<td>15</td>
<td>9.0</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Friedman Two-Way Analyses of Variance (Siegel, 1956) were performed on the data of each observer separately. The numbers used in the analyses were the actual magnitude estimation numbers instead of the logarithm of these numbers (see Chapter IV). The Friedman test requires only ordinal scale of measurement; the logarithmic transformation preserves transitivity. The results of the analysis were significant ($p < 0.001$) for both observers. For observer 1, $X^2_R = 36.1$; for observer 2, $X^2_R =$
Following this result, pairwise comparisons for the data for each stimulus for each observer were performed using the Wilcoxon Matched-Pairs Signed-Ranks test (Siegel, 1956), in order to determine which of the stimuli differed significantly. The results of the comparisons are shown in Table 7.

Table 7

Pairwise comparisons of the ratings of apparent brightness of each stimulus by observer 1, O1, and observer 2, O2, using the Wilcoxon Matched-Pairs, Signed-Ranks test. Stimuli which do not differ significantly (p > 0.5) are joined by a straight line.

<table>
<thead>
<tr>
<th>Masking Stimuli</th>
<th>O1</th>
<th>SR</th>
<th>15</th>
<th>10</th>
<th>2.5</th>
<th>Gate</th>
<th>Batman</th>
<th>5</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>O1</td>
<td>SR</td>
<td>15</td>
<td>10</td>
<td>2.5</td>
<td>Gate</td>
<td>Batman</td>
<td>5</td>
<td>SA</td>
</tr>
<tr>
<td></td>
<td>O2</td>
<td>SR</td>
<td>15</td>
<td>Batman</td>
<td>Gate</td>
<td>10</td>
<td>2.5</td>
<td>5</td>
<td>SA</td>
</tr>
</tbody>
</table>

Following a suggestion by McGuigan (1968), the stimuli which do not differ significantly (p > 0.05) are joined by a straight line. Stimuli which differ significantly (p < 0.05) are not so joined. Both observers rated the Sine R and the 15 c/d stimuli as less bright than other stimuli. This result is expected of the Sine R stimulus which had significantly less luminance than the other stimuli. The 15 c/d stimulus, however, was significantly attenuated. This means that any masking caused by the presence of the 15 c/d mask is probably attenuated in amplitude by a related factor. Observer 1 also
rated the 10 c/d as not significantly different from the Sine B and 15 c/d stimuli; however, as can be seen in Table 6, this is due, in part, to observer 1's comparatively high rating for the Sine R stimulus, 3.7. It is interesting that observer 1 rated the 2.5 c/d and 5 c/d stimuli as not significantly different in apparent brightness from the Gate and Batman stimuli whereas observer 2 rated the 2.5 c/d, 5 c/d and Sine A stimuli, together with the 10 c/d stimuli as significantly different from Gate and Batman. What distinguishes the 2.5 c/d, 5 c/d and Sine A stimuli is that they have a greater amount of brightness concentrated in the center of the stimulus than do any other stimuli. This suggests that the two observers differed in their criteria of rating the apparent brightness of the targets during masking. Observer 1 seemed to base his ratings of apparent brightness on a space average of luminance across the entire width of the stimulus, except for the Sine A stimulus. Observer 2, on the other hand, seemed influenced to a greater extent by the center of the stimulus. This observation is consistent with the differences in masking amplitudes between the two observers which will be considered in Chapters IV and V. The amounts of masking for the data of observer 2 were consistently greater than were the amounts of masking for the data of observer 1. In this masking study and in previous studies (Growney & Weisstein, 1972; Cox, Growney & Weisstein, in preparation), observers have commented that the center of the
stimulus is often occluded by the masking stimulus while the
dges of the stimulus remain. If an observer were to base his/
er criteria on the center portion of the stimulus rather than
a space average across the entire width of the stimulus, then
the data from that observer would probably show increased
amounts of masking.

It is difficult to decide the extent to which this compari-
son of the different kinds of stimuli can be utilized to adjust
the masking data. Sine A and Sine R were at opposite ends of
the apparent brightness rating scale (see Table 7) but were
quite similar in their effectiveness as masking stimuli (see
Chapter IV). The situation is not improved if attention is re-
stricted to the frequency stimuli. On the one hand, most of
the attenuation of the 15 c/d mask was probably due to peri-
pheral processing mechanisms and not to higher order neural
mechanisms. Patel (1966) found that the neural line spread
functions for a detection task were narrow in comparison to the
optical line spread. However, these neural transfer character-
istics were obtained using a detection response measure and
Westheimer and Campbell's (1962) estimate of the optical line
spread function. Campbell and Gubisch (1966) obtained much
narrower estimates of the width of the optical line spread
function. Patel's (1966) measure of the width of the neural
line spread function is probably an under estimate because too
much attenuation was attributed to the optics of the eye. On
the other hand, some of the attenuation of the 15 c/d mask and
other stimuli was probably due to higher-order neural mechanisms, some of which may have also contributed to the masking effect. For these reasons, the data were not adjusted with respect to the comparison of the stimuli. This is probably not a critical point because the metacontrast effect is not readily influenced by small fluctuations in luminance (Weisstein, 1972). The extent to which masking differences can be attributed to differences in the stimuli based on this comparison of stimuli is indeterminate although probably small. At the least, any masking obtained with the 15 c/d mask in particular is probably an underestimate. As will be seen in Chapter V, this will not be a crucial factor in testing any of the models of spatial frequency in metacontrast.

Comparison of the Contrast of the Stimuli

In addition to the comparison of the apparent brightness of the stimuli, the frequency-modulated stimuli, Gate, 2.5 c/d, 10 c/d, and 15 c/d were rated in terms of their contrast. The 5 c/d stimulus was assigned a modulus of 10; it is assumed that the mean rating of the 5 c/d stimulus would have been 10. Other details of the presentation of these stimuli, such as which stimuli were used, randomization, and number of replications are identical to the conditions for the comparison of the apparent brightness of the stimuli. The geometric means for each stimulus are plotted in Figure 16. Pairwise comparisons of the data for each stimulus were performed using the Wilcoxon Matched-
Fig. 16. Magnitude estimations of the contrast of the frequency-modulated stimuli for the two observers. Observer 1, •--•, and observer 2, •--•. Each point is the geometric mean of 10 replications.

Pairs, Signed-Ranks test with a significance level, p = 0.05. For both observers, the 15 c/d stimulus (and the Gate stimulus, by definition) was significantly reduced in contrast as compared to the other stimuli. The 10 c/d stimulus was also significantly different from the other stimuli for the data of observer 1. However, the other stimuli, the 2.5 c/d, 5 c/d, and 10 c/d stimuli for observer 2, and the 2.5 c/d and 5 c/d stimuli for observer 1, did not differ significantly from one another.

These results are interesting because they resemble the masking results for the 5 c/d target using each of these frequency-modulated stimuli as masks (see Figure 54 in Chapter V). The
data for the 5 c/d target for observer 1 are at a maximum for
the 2.5 c/d mask whereas for observer 2 they are at a maximum
for the 5 c/d mask. The relative differences between the data
of the two observers for the 5 c/d, 10 c/d, and 15 c/d masks
are also preserved between this contrast comparison of the
stimuli and the masking data for the 5 c/d target. The major
discrepancy is that the amount of masking obtained with the
Gate mask is much greater than that predicted by its zero con-
trast. This similarity between the contrast of the masking
stimuli and the masking data obtained using these same stimuli
will be discussed in Chapter V.

The contrast ratings of the two observers are also inter-
esting in that the ratings follow the contrast sensitivity
curve for human vision (e.g., Davidson, 1968). The ratings
show low contrast at low frequencies, peak contrast from 2.5 to
5 c/d, and a drop-off in frequency for higher frequencies.
This general correspondence implies that the contrast of the
aperiodic stimuli was not distorted with respect to the contrast
shown in studies of periodic gratings.

In order to determine the general relationship between
the apparent brightness ratings and the contrast ratings of the
5 c/d target, pairwise comparisons of the two ratings for each
stimulus condition in the experiment were performed using t-
tests on the logarithms of the magnitude estimations (cf.,
Chapter IV). The magnitude estimation numbers for one com-
parison consisted of the geometric means for the 11 ISIs for one
target-mask-separation condition. None of the results of the 30 t-tests on the data of each observer were statistically significant, \( p > 0.05 \) in all cases. A second set of t-tests were performed on these data on the assumption that the small amount of masking which occurred at large separations might have hidden, in effect, any significant differences between the contrast ratings and apparent brightness ratings. These pairwise comparisons were identical to the first set of comparisons with the exception that the data for the ISIs larger than 120 msec. were omitted from the analyses. None of the 10 t-tests for any of the target-mask combinations at the first two separations (1' and 4') for the data of each observer were statistically significant (\( p > 0.05 \)). Of the remaining 20 t-tests performed on the data of observer 1, 4 comparisons were statistically significant: the Gate mask at a separation of 12' (\( p < 0.01 \)) and a separation of 24' (\( p < 0.05 \)), the 2.5 c/d mask at a separation of 12' (\( p < 0.02 \)), and the 15 c/d mask at a separation of 24' (\( p < 0.05 \)). Of the remaining 20 t-tests performed on the data of observer 2, only 2 comparisons were statistically significant: the 5 c/d mask at a separation of 84' (\( p < 0.05 \)), and the 10 c/d mask at a separation of 24' (\( p < 0.05 \)). Because these statistically significant comparisons are so few, are different for the two observers, and occur for separations at which the magnitude of the masking effects are quite small, it is quite possible that the significance of these results is due
to chance. The apparent brightness ratings will be used ge-
erally in all analyses which follow (though, see Chapter V, for one exception) because of the similarity between the apparent brightness and contrast ratings in the data.
CHAPTER IV

RESULTS FOR THE EDGE HYPOTHESES

A preliminary examination of the data showed that the individual results for the two observers are dissimilar in amount of masking (see Figure 26) and several other overall characteristics (see Figure 27). Individual differences with respect to the magnitude of psychophysical estimates of the effectiveness of a variety of stimuli was not unexpected (Teller and Lindsey, 1970). It is unclear whether such differences are simply parameter variations of simple neural mechanisms or whether these differences are a function of more complex information processing mechanisms. The data of the two observers, therefore, were not averaged.

Separate analyses of variance were performed on the data of the two observers. Because magnitude estimations tend to give log-normal distributions (Stevens, 1966), the analyses were performed on the logarithms of the data. The statistical model for the analysis of variance was a fixed constants model with m replications per cell for n = 1 (McNemar, 1962). The error term for this model is the error due to within cell replicates. Although the results for such an analysis are non-generalizable to the population of observers, the statistical results specify the statistical significance of the individual observer's performance, thereby suggesting which variables and
variable relationships are important for the development of a
generalizable theory.

A four-way analysis of variance (target X mask X separation X ISI) was performed on the brightness ratings of each observer for the stimuli differing principally in edge gradient: Sine R, Sine A, Gate, and Batman. All main effects and interactions were significant ($p < .01$). These statistical results will be discussed where pertinent in the following analysis.

**General Characteristics of the Data**

The data for the two observers are shown in Figures 17-32. Each graph represents the data of an observer for a particular target-mask combination. Each line within a graph represents the data for a particular target-mask separation. Each point in each graph represents the geometric mean over eight replications. The graph of the data of observer 1 for a particular target-mask combination is on the left; the corresponding graph for observer 2 is always on the right. The first four graphs depict the results for the Sine R target with the Sine R mask (Figure 17), the Sine A mask (Figure 18), the Gate mask (Figure 19) and the Batman mask (Figure 20). The second set of four graphs depict the results for the Sine A target with the same four masks in the same order (Figures 21 through 24), followed by a similar treatment for the Gate and Batman targets (Figures 25 through 32).

In general, the data for the two observers possess similar
Fig. 17. Magnitude estimations of the Sine R target with the Sine R mask as a function of temporal interstimulus interval (ISI). Each line displays the results for one of the six spatial separations of target and mask: 1', ⋄; 4', △; 12', +; 24', X; 48', ○; and 84', ◦. The results for observer 1 are shown on the left; the results for observer 2 are on the right.
Fig. 13. Magnitude estimations of the Sine R target with the Sine A mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 19. Magnitude estimations of the Sine R target with the Gate mask as a function of temporal interstimulus interval (ISI). Other details as in figure 17.
Fig. 20. Magnitude estimations of the Sine R target with the Batman mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 21. Magnitude estimations of the Sine A target with the Sine R mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 22. Magnitude estimations of the Sine A target with the Sine A mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 23. Magnitude estimations of the Sine A target with the Gate mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 24. Magnitude estimations of the Sine A target with the Batman mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 25. Magnitude estimations of the Gate target with the Sine R mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 26. Magnitude estimations of the Gate target with the Sine A mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 27. Magnitude estimations of the Gate target with the Gate mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 28. Magnitude estimations of the Gate target with the Batman mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 29. Magnitude estimations of the Batman target with the Sine R mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 30. Magnitude estimations of the Batman target with the Sine A mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 31. Magnitude estimations of the Batman target with the Gate mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
Fig. 32. Magnitude estimations of the Batman target with the Batman mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 17.
characteristics for the edge gradient stimuli. The amount-vs-ISI masking curves for the two observers vary in a similar manner as a function of target edge gradient, mask edge gradient, separation and ISI (to be described below). There are obvious dissimilarities, however. Observer 2 gave consistently higher brightness ratings as compared to observer 1. This difference can be seen in many of the figures, for example, Figures 27, 28, 31 and 32. An expected result of this amplitude difference in the responses of the two observers is that the masking curves for observer 1 should be lower and, therefore, show a narrower range of masking across ISI as measured by the width of the curve. The masking curves for observer 1, however, are not simply lower in height (amount of masking) but different in shape; they are shaped more like a V than the rounded U shapes describing the data for observer 2. This means that observer 1 has a narrower temporal range of ISI over which masking can occur than does observer 2.

A comparison of Figures 17 through 32 shows that the amount of masking obtained for a particular target-mask combination differs greatly, depending on the edge gradient of both target and mask. The amount of masking depends on the edge gradient of the target. This effect is statistically significant (main effect of target) and can be seen by comparing the results of different targets for the same mask (for example, Figures 20, 24, 28 and 32). Masking increases for the constant
mask as target edge gradient increases. The importance of the mask edge gradient can be observed by comparing the results of different masks for the same target (for example, Figures 25, 26, 27, and 23). Masking increases for the constant target as mask edge gradient increases. The main effect of mask is also significant statistically.

Little masking is obtained where both the target and mask are Sine stimuli. For these cases the masking function for amount-vs-ISI is approximately a straight line; masking does not increase or decrease as a function of ISI. For other cases, particularly for the cases where Gate or Batman are targets, masking does vary as a function of ISI and is a significant effect (main effect of ISI). Little masking is obtained for either simultaneous presentation of target and mask or for large time delays between target and mask. Maximum masking is obtained at ISIs for which the target preceded the mask by 20 to 30 msec. These characteristics describe a U-shaped masking function and are expected in a metacontrast experiment (e.g., Alpern, 1953). The data show that this masking effect is also a function of edge gradient.

The amount of masking obtained is also a function of the separation between target and mask. Most masking is obtained when the mask is close to the target at a separation of one minute visual angle. The height of the masking curve is greatest for this condition. As distance between the target
and the mask increases, amount of masking falls off rapidly; however there is some masking, nearly zero, at a separation of \( \delta_4' \). These effects are shown for the data of the two observers for the Gate target in Figure 33; this is a plot of the peak masking point for each amount-vs-ISI masking curve as a function of target-mask separation. The peak masking point at a particular ISI is chosen as a measure of the masking effect for a particular target-mask condition because this point represents the optimal suppression effect of each mask on the target. The changes in masking as a function of separation between target and mask are statistically significant (main effect of separation).

The Sine targets show little masking regardless of separation (see Figure 33). The Gate and Batman targets, on the other hand, show a great deal of masking at small separations of target and mask. This differential effect of targets across separation is a significant one (target X separation interaction). The masks also show significant differences across separation (mask X separation interaction). The Sine masks show little masking regardless of separation whereas the Gate and Batman masks are effective at small separations (see Figure 33). The effectiveness of the Gate and Batman mask also depends on the target, however. Generally, the Sine stimuli are very resistant to masking regardless of the mask and are relatively ineffective as masking stimuli. On the other hand, stimuli with pronounced edge gradients, Gate and Batman, can be
Target Mask Separation (In Minutes)

Fig. 33. Greatest masking values (peak masking) at a particular ISI as a function of target-mask separation for the Gate target with various masks. Sine R—•; Sine A —•; Gate Δ—Δ; and Batman o—o. (a) Data of observer 1; (b) data of observer 2. Zero denotes complete masking; 10 denotes no masking.
strongly masked (e.g., Figures 28 and 32) but only by masks with pronounced edge gradients (see Figure 33). Similarly, stimuli with pronounced edge gradients are very effective as masking stimuli (e.g., Figures 28 and 32), but only for targets with pronounced edge gradients (see Figure 33). The interaction of targets and masks is statistically significant (target X mask interaction) and has differential effects across separation. This significant effect can be observed in Figure 33 by comparing the results for different target-mask combinations at small and large separations (target X mask X separation interactions).

Examination of the Target-Mask Interaction

Masking is not simply a function of the target edge gradient alone or even the mask edge gradient alone. Both of these main effects, of target and mask, are important. It is apparent from the data, however, that the amount of masking which is obtained differs greatly for different target-mask combinations (see Figure 33). Sine stimuli are relatively ineffective as targets or masks whereas Gate and Batman are quite vulnerable to masking and also serve as very effective masking stimuli. This effectiveness of the Gate and Batman stimuli is apparent chiefly only in interaction with other Gate or Batman stimuli. Because Gate and Batman differ from Sine stimuli in strength of edge gradient, the pronounced effectiveness of the interaction between edged stimuli suggests that metacontrast is a function of target-mask edge interaction. To examine this
hypothesis in more detail, the data will be compared to various models of edge activity in metacontrast.

The values representing the greatest amount of masking at a particular ISI will be used to represent the optimal masking effect for a given target-mask combination (cf., Growney & Weisstein, 1972). To simplify the comparison for different targets-mask combinations, only the results for the smallest separation between target and mask will be examined; this is the condition for which maximum masking is obtained. These data are shown in Table 8. To compare conveniently the predictions of the models with the data, these data (values representing the greatest amount of masking) were inverted (subtracted from 10) so that more masking would correspond to a larger number, and then normalized. The normalizing constant was the value of greatest masking, which, for both observers, was obtained for the Gate target—Batman mask combination. These inverted, normalized data are shown in Table 9.

To judge the relative effects of different luminance gradients at the edge of the mask, the values representing the greatest amount of masking for each mask for a given target are plotted in Figure 34. These graphs display the data in the rows of Table 9. The limits of ±1 standard error are shown for each normalized data point. Each standard error was normalized with the same constant used for the data. These standard errors are based on the arithmetic standard deviations of the
Table 8

Values representing the greatest amount of masking for each target-mask combination at 1\' separation for the data of the two observers. Observer 1, 01, and observer 2, 02. A zero means the target was completely occluded; a ten means the target matched the standard in appearance.

<table>
<thead>
<tr>
<th>Targets</th>
<th>Masks</th>
<th>Sine R</th>
<th>Sine A</th>
<th>Gate</th>
<th>Batman</th>
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data. Strictly speaking, a measure like a geometric standard deviation should have been used. The numbers obtained from such a calculation, however, are quite small and rather misleading as to the amount of variability of the data. The range of normalized standard error for observer 1 is from 3 to 17 percent with most values at or below 11 percent. For observer 2, the range is from 3 to 11 percent with most values at or below 8 percent. These values describe the variability of magnitude estimations at the ISI for peak masking. In part this
Normalized, inverted values representing the greatest amount of masking for the data shown in Table 8. Observer 1, 01 and observer 2, 02. The value, 1.0, corresponds to the masking response of greatest magnitude across conditions for each observer independently. A zero now means no masking occurred.

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<th>Sine A</th>
<th>Gate</th>
<th>Batman</th>
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Variability is due to the difficulty of the observer's task. At the ISI at which the greatest amount of masking occurred, the target is effected in a multiplicity of ways including fragmentation and apparent motion. To describe the changes in the target as brightness changes is at best an approximate procedure.

All masks are fairly ineffective in masking the Sine R and Sine A targets. The differences between the masks is apparent in Figure 34 (c and d). The masking of the Gate target
Fig. 34. Normalized values representing the greatest amount of masking (peak masking) for the inverted data at a target-mask separation of 1° for a given target for the four masks. The standard error, ±1, is shown for the data of observer 1, o—o, and observer 2, Δ—Δ, for each of the four targets; (a) Sine R, S_R; (b) Sine A, S_A; (c) Gate, G; and (d) Batman, B.
is an increasing function of mask edge gradient. The masking of the Batman target is similar but not as regular as the masking of the Gate target. Most masking of either target is obtained with the Batman mask. This result suggests that mask contour information is important for the masking effect to occur.

In general, the Sine R and Sine A targets were masked little with a slight trend of increased masking with increased mask edge gradient. A comparison of Figure 34 (a and b) with Figure 34 (c and d) suggests that targets without edges are not masked. This is a restatement of the statistical main effect of target but is of interest because the statement emphasizes that target contour information is required for the masking effect to occur. One alternate possibility, however, is that the Sine targets were not processed as Sine stimuli but as narrow Gates. Perhaps the visual system does not process the shallow sloped edges of Sine but only processes the center of the Sine stimulus. This means that the Sine stimuli would really be processed as narrow Gates at some distance from the other stimuli. Masking falls off as distance between target and mask increases; hence, reduced masking would be predicted for the Sine stimuli as compared to the Gate and Batman stimuli.

To evaluate this possibility, assume that the center half (24') of the Sine target is processed as a narrow Gate. The masking of the Sine target by a Gate mask at one minute separation between target and mask, then, should be equal to the
masking of the Gate target by a Gate mask at 12' separation. This result is expected even though the Sine stimulus Gate would only be half the width of the regular sized Gate stimuli. If any difference in masking between the two conditions occurred because of target size, the smaller Sine stimulus Gate should be masked more easily (cf., Growney & Weisstein, 1972). The values for these stimulus combinations are shown in Table 10. The data for observer 1 show no difference between the two conditions. The value representing the greatest amount of masking for the Gate target-Gate mask combination at 12' separation is 8.0 whereas the Sine R-target-Gate mask at 1' separation is 7.2 and the Sine A-target-Gate mask at 1' separation yields 8.6. The data for observer 2, however, clearly contradict the hypothesis that Sine stimuli are processed as narrow gates of 24' width (width value for the most conservative test). The value of the Gate target-Gate mask masking result at 12' separation is 4.6 whereas the Sine R target-Gate mask masking result at 1' separation is 7.7 and the Sine A target-Gate mask masking result at 1' separation is 7.3.

To judge the relative effects of different luminance gradients at the edge of the targets, the values representing the greatest amount of masking of each target by a given mask are plotted in Figure 35. These graphs display the data in the columns of Table 9. The Sine stimuli are more effective as masking stimuli than they are as target stimuli. The differential
The data representing the greatest amount of masking for each stimulus combination at target-mask separations of 1' and 12' of visual angle for the data of the two observers. (a) observer 1 and (b) observer 2. The data are magnitude estimations

(a) 

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(b) 

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<tr>
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<td>12'</td>
<td>8.4</td>
<td>8.1</td>
<td>4.6</td>
<td>4.3</td>
</tr>
</tbody>
</table>
effects of the Sine masks are present in the data of both observers. The Sine masks are surprisingly effective in masking the Gate and Batman targets for observer 2. Because of the normalization of these plotted data, the difference cannot be attributed to general amplitude differences between the two observers but represent real differences in observer 2's data. The results of the two observers for the Sine A mask are fairly parallel except for the differences with the Sine targets. The results of the two observers for the Sine R mask are similarly identical except for the difference with the Batman target.

Masking increases greatly with the Gate mask for the Gate and Batman targets. This is also true for the results with the Batman mask. This means that targets with pronounced edge gradients are more vulnerable to the masking effect; this result implicates the target edge gradient in the metacontrast effect. In fact, the metacontrast effect seems described best as a target-mask edge interaction.

The Sine R and Sine A masks are much less effective as masking stimuli than are the Gate or Batman masks (cf. Figures 35a and 35b with 35c and 35d). The Sine A mask is slightly
Fig. 35. Normalized values representing greatest amount of masking (peak masking) for the inverted data at target-mask separation of 1' for a given mask for the four targets. The standard error, ±1, is shown for the data of observer 1, - - - , and observer 2, Δ--Δ, for each of the four masks: (a) Sine R, $S_R$; (b) Sine A, $S_A$; (c) Gate, G; and (d) Batman, B.
more effective than the Sine R mask which might be expected because of the increased edge luminance in Sine A as compared to sine R. Neither mask, however, is very effective. Both stimuli have only a small amount of luminance at their borders as compared to Gate or Batman. This result suggests that stimuli without edges are not effective masking stimuli.

It is possible here also that the Sine stimuli are processed as Gates of 24' width at some distance (12') from the target. This would require that the amount of masking obtained with the Gate target-Sine mask at a target-mask separation of 1' should be identical to the data for the Gate target-Gate mask at a separation of 12'. Again, the data of observer 1 supports this interpretation but the data of observer 2 contradicts it (see Table 10). An additional argument against this interpretation will be presented later.

Models of Edge Activity in Metacontrast

Because of the strong target-mask interaction in the data of both observers, metacontrast may involve edge interaction between the target and mask. To specify what stimulus characteristics about the edges of the target and mask are important in this interaction, the data were compared to several models of edge activity. It is doubtful that a single model will predict the results for a stimulus both as target and mask. The edge information of the target and mask are probably evaluated in different ways in visual processing. This suggestion is
supported by the differences (nonreciprocity) displayed in Figures 34 and 35 between the results for a particular stimulus as target (Figure 34) and that same stimulus as mask (Figure 35).

One explanation of the masking effect is that the masking is directly related to the amount of mask luminance at the edge of the mask near the target. A Batman mask adjacent to the target, for example, would be more effective than the Gate mask adjacent to the target as a masking stimulus because Batman has a greater concentration of stimulus intensity within several minutes of visual angle near its edge. To evaluate the hypothesis, the formulae describing the stimuli (stimulus intensity with respect to distance) were integrated over various limits measured from the edge of the mask. Several values of integration limits were chosen because it is unclear what an edge means to the visual system. An edge might mean luminance within one minute or 10 minutes of the edge of the mask close to the target. As one method of treating this uncertainty, several limit values were tested. The limits of integration which were selected were 2', 3', 4', 8' and 11' of visual angle. The resulting areas (amount of stimulus intensity) which were computed for each of the four stimuli were normalized with respect to the largest of the four areas for that particular integration limit; these normalized values are presented in Figure 36. Each line represents the
Fig. 36. Normalized areas describing stimulus luminance within x minutes of the edge of the stimulus for several values of x. x = 2', o--o; 3', △-△; 4', a--a; 3', e--e; and 11', ▲--▲. Masks: Sine R, S_R; Sine A, S_A; Gate, G; and Batman, B.

The results for a particular limit of integration. None of the lines fit any of the data in Figure 35 very well. Masking does not seem to be directly related to luminance. However, the lines do follow some of the general characteristics of the data. Masking may not be unrelated, therefore, to luminance. It is interesting that, for all limits of integration larger than 2', the luminance model predicts that the Batman stimulus should be more effective as a mask than the Gate stimulus. For the 2' limit, however, the model predicts that the Gate stimulus should be more effective than the Batman stimulus. This prediction is due to the fact that the Gate stimulus intensity rises rapidly as a step in luminance whereas the Batman stimulus intensity
rises more gradually. The Gate stimulus, therefore, has more luminance at its edge; the Batman stimulus has more luminance within several minutes of its edge.

A model closely related to the above is to relate masking to the logarithm of stimulus intensity. This hypothesis is a likely possibility because there is evidence that a logarithmic transformation of stimulus information occurs early in the visual pathway. The effectiveness of a particular mask, then, might be related to the logarithm of intensity at its edge. The same procedures were followed as for the first model with the exception that the integration over various limits was performed with respect to \( \ln[f(x)] \) rather than simply \( f(x) \). The results of this integration are displayed in Figure 37. Again, none of the possible predictions fit any of the data in Figure 35 very well. The data show a much greater difference between the Sine stimuli and the two edge stimuli (Gate and Batman) than are predicted by the model. Neither do the predictions fit the data in Figure 34. The data of observer 2 for the results of different masks with the Batman target fit best but the model predicts that the edged stimuli should be more alike than they are in the data. In general, the data do not fit a model of masking as directly related to the logarithm of stimulus intensity.

One model of the interaction of target and mask in meta-contrast is an application of the observations of Land and McCann (1971). The hypothesis is that the effect of the mask
Fig. 37. The same as Figure 36 except the normalized areas describe the logarithm of stimulus luminance within x minutes of the edge of the stimulus on the target can be predicted by the product of the maximum/minimum ratios about the edges of the target and mask. To evaluate this hypothesis, the following steps were taken.

1. The maximum/minimum ratios are assumed to be formed subsequent to some stage or stages in visual processing which can be described by the convolution of the stimulus function with a neural spread function or weighting function. This spread function is assumed to describe the lateral inhibition characteristics of the operative neural mechanism. The actual spread function that was used in this study is described by Campbell, Carpenter and Levinson (1969) for the behavior of the visual system at threshold. This function was chosen simply as representative of hypothesized higher-order neural processing.
The function, \( S(x) \), is of the form,

\[
S(x) = \frac{K}{\pi} \left[ \frac{a}{a^2 + x^2} - \frac{b}{b^2 + x^2} \right]
\]

where \( a = 0.0375656 \) and \( b = 0.0425921 \). (2) The spread function, \( s(x) \), was convolved with each of the stimulus functions in steps of \( x = 0.001 \) degrees between \( x = -0.05 \) and \( +0.05 \) degrees. (3) The assumption was made that the maximum in Land and McCann’s ratio was equal to the integral of the convolved function over a small area corresponding to the area immediately inside the edge of the stimulus function. Similarly, the minimum was assumed to equal the integral over a small area of the convolved function corresponding to the area just outside the edge of the stimulus function. Two limits of integration were chosen, 2' and 4' of visual angle as estimates of information near the edge of the stimulus. Each integral was normalized with respect to the largest integral for that particular limit of integration for the four stimuli. In this way, two ratios were formed: the 2' maximum/minimum ratio corresponding to the integral over 2' on either side of the point corresponding to the edge of the stimulus, and the 4' maximum/minimum ratio corresponding to the integral over 4' on either side of the point corresponding to the edge of the stimulus. These two ratios for a particular stimulus, such as a Gate, represent two possible kinds of information about that stimulus at some level in neural processing. (4) The hypothesis, then, is that mask-
is proportional to the product of the ratios comprising the neural edge description of the target and masking stimuli. Consider a Batman target with a Gate mask. Masking of the Batman target should be proportional to the product of either the 4' ratios representing the neural edge information about the edges of the two stimuli or to the product of the 2' ratios. These products are listed in Table 11. The table implies that masking ought to be symmetrical; that is, the masking of the Batman target by the Gate mask should be equal to the masking of the Gate target by the Batman mask.

The predictions of the model, however, do not fit the data. The model predicts that the Batman target-Batman mask stimulus combination should yield the greatest masking effect, but this is contrary to the data (see Figure 35). According to the model, the Batman target should always show more masking than the Gate target; Sine A should always yield more masking than the Sine R target. Again the data do not follow this prediction. Finally, the model predicts that masking effects should be symmetrical for two different stimuli as target and mask but such symmetry is not evident in the data (see Figures 34 and 35).

A fourth hypothesis is that the amount of masking is directly related to the weighted mask luminance near the edge of the mask. Growney and Weisstein (1972) found that the decrease in brightness of a Gate target for masks of varying
Table 11

Product of the maximum/minimum ratios for each target-mask combination for (a) 2' and (b) 4' of visual angle about the edge of each stimulus.

(a)

<table>
<thead>
<tr>
<th>Targets</th>
<th>Masks</th>
<th>Sine R</th>
<th>Sine A</th>
<th>Gate</th>
<th>Batman</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine R</td>
<td>0.0686</td>
<td>0.074</td>
<td>0.168</td>
<td>0.262</td>
<td></td>
</tr>
<tr>
<td>Sine A</td>
<td>0.074</td>
<td>0.079</td>
<td>0.181</td>
<td>0.282</td>
<td></td>
</tr>
<tr>
<td>Gate</td>
<td>0.168</td>
<td>0.181</td>
<td>0.415</td>
<td>0.643</td>
<td></td>
</tr>
<tr>
<td>Batman</td>
<td>0.262</td>
<td>0.282</td>
<td>0.643</td>
<td>1.000</td>
<td></td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>Targets</th>
<th>Masks</th>
<th>Sine R</th>
<th>Sine A</th>
<th>Gate</th>
<th>Batman</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine R</td>
<td>0.047</td>
<td>0.052</td>
<td>0.199</td>
<td>0.216</td>
<td></td>
</tr>
<tr>
<td>Sine A</td>
<td>0.052</td>
<td>0.058</td>
<td>0.223</td>
<td>0.242</td>
<td></td>
</tr>
<tr>
<td>Gate</td>
<td>0.199</td>
<td>0.223</td>
<td>0.850</td>
<td>0.923</td>
<td></td>
</tr>
<tr>
<td>Batman</td>
<td>0.216</td>
<td>0.242</td>
<td>0.923</td>
<td>1.000</td>
<td></td>
</tr>
</tbody>
</table>

widths could be described by a weighting function. The luminance of the mask edge which was closest to the target edge contributed more to the masking effect than did luminance 4' to 5' from the target edge. Luminance at a distance of 10' contributed little to the masking effect. The weighting functions of each of the three observers in that study for the monoptically-presented, 49' wide target were averaged. A straight-line approximation for these averaged weights is shown in Figure 33. This function was convolved with each of the stimulus functions over several limits of integration: 2', 3', 4', 3', and 11' of visual angle. Several values of integration limits were chosen on the assumption that the weighting function might well differ
in width for individual observers. The observers in the Growney and Weisstein study (1972) had weighting functions which were similar in width; other studies, however, (e.g., Matthews, 1971) suggest that this similarity need not always occur. To provide some freedom in the model for specifying the spatial extent of the weights, the convolution was performed for different limit values. The results of the convolution for the four stimulus functions were normalized with respect to the largest of the four areas for that particular integration limit. These normalized values are displayed in Figure 39. If the amount of masking corresponds to weighted mask luminance near the edge of
Fig. 39. Normalized areas describing the convolution of the weighting function with the stimulus functions within x minutes of the edge of the stimulus for x and the masks described as in Figure 36.

the target, then one set of these normalized values should fit the data. The closest fit of the model to the characteristics of the data occurs with the results of the various masks for the Gate target. This comparison is graphed in Figure 40. The data of observer 1 correspond most closely to the set of normalized values obtained by integrating over 4' near the edge of the target. All weighting function points are within one standard error of the data points except for the Sine R mask. The data of observer 2 correspond best to the values obtained by integrating over 3' near the edge of the target. The fit is not good since only the weighting function points for the Batman and Gate masks are within one standard error of the data points. However, the differences for the Sine A and Sine R
Fig. 40. Comparison of the data of the two observers with the convolution of the weighting function and stimulus functions for two limit values of visual angle within each mask for the Gate target. Observer 1, •••; observer 2, ▲▲▲. Limit values: 4', ■■■; 3', ▲▲▲.

Masks are small as they are for the Sine R mask for observer 1. It is possible that the weighting function applies only to stimuli with well-defined edges. More masking was obtained with the Sine stimuli than was predicted by weighted edge luminance (with the exception of observer 1 with the Sine A mask). More importantly, the general characteristics of the weighting function curve are similar to the general characteristics of the data, especially in comparison to the characteristics of the luminance and log luminance models. Because of this general similarity, it is more likely that the three differences between the predicted and obtained points are due either to differences in
individual weighting functions or to an inappropriate application of the weighting function model to stimuli with little edge luminance.

It is interesting that the model fits best the results for the Gate target. The weights in the Growney and Weisstein (1972) study were obtained for a Gate target of the same width as the Gate target in this study. This result suggests that these weights describe how mask edge information is processed in the masking of the Gate target. The edge gradients in this study are unlike those of the Growney and Weisstein (1972) study, yet the weighting function is still of some predictive value. However, these weights seem to be specific to a Gate target and do not predict mask edge information processing for targets with different edge gradients. Because the data of this study support the hypothesis that metacontrast is an interaction between the edge information of both target and mask, it is not too surprising that weights obtained in a metacontrast experiment are target specific. A specific interpretation of the meaning of these weights has been suggested recently by Shapley and Tolhurst (1973). Using the psychophysical technique of subthreshold addition of various luminance patterns to an edge, Shapley and Tolhurst described the sensitivity of an antisymmetric mechanism which, as they comment, is remarkably similar to the profile (weights) determined by Growney and Weisstein (1972). This mechanism is
interpreted by Shapley and Tolhurst as an antisymmetric edge
detector, similar to those described by Hubel and Wiesel (1962)
for the cat striate cortex. The fit of the predictions based
on the weighting function to the data of this experiment are
consistent with the edge detector hypothesis. More importantly,
if it is assumed that such a mechanism is centered at the edge
of the target, the output of the mechanism is jointly effected
by both the target contour and mask contour information. The
antisymmetric device would be excited by the target contour in-
formation and inhibited by the mask contour information (e.g.,
see Figure 2 in Shapley and Tolhurst, 1973). The predictions
for metacontrast based on such a device would be (1) for a con-
stant target, the greater the luminance at the edge of a mask,
the greater should be the amount of masking; and (2) for a con-
stant mask, the greater the luminance at the edge of the target,
the smaller should be the amount of masking. The first pre-
diction (1) is qualitatively supported by the data of this
experiment (see Figure 34), with the exception of the Sine R
mask with the Batman target for observer 2. The amount of mask-
ing of a constant target increases with increasing mask edge
luminance. The second prediction (2) is not even qualitatively
supported unless it is assumed that the edge detector has a
threshold which is not exceeded with the Sine stimuli. Given
this assumption, the second prediction is qualitatively supported
(see Figure 35) with the exception of the relationship between
the Gate target and Batman target to the Gate mask for observer 1. The amount of masking is smaller for the Batman target than it is for the Gate target in three of the four possible cases with the Gate and Batman masks.

To characterize the interaction of the target and mask edge information quantitatively, it would be helpful to know how the weighting function varies as a function of target edge gradient for a particular mask for a particular observer. If the effectiveness of masks for a target of any edge gradient can be described by a specific weighting function, then, at least, the important characteristics of the masking stimulus could be identified as the weighted mask luminance near the edge of the target. For example, the masking of the Gate target might be described by one weighting function while the masking of the Batman target might be described by a different weighting function. The function of the mask information in visual processing would at least be specified as a preliminary step to specifying the target-mask interaction system. The value of this proposal is based in part on the assumption that the differences between the data in Figure 40 for the two observers is due only to individual weighting function differences, differences either in the magnitude or spatial extent of the weights.

Although the weighting function may describe the manner in which information about the edge of the mask is processed in
the visual system, the function does not describe how information about the edge of the target is processed. A possible exception to this statement is that the results for various targets with the Batman mask (see Figure 35d) compare favorably to the set of normalized values for the integral of weighted target luminance over 2' of visual angle near the edge of the target. The fit is not especially good in that the greatest amount of masking obtained for the Sine R and Sine A targets are closer to one another than are predicted by the weighted luminance model. In fact, what seems to characterize the results of the targets for a constant mask, especially for the Gate and Batman masks, is that the results for the Sine R and Sine A targets are very close to one another as are the results for the Gate and Batman targets. These characteristics could be due to several different edge factors other than the integral of weighted target luminance near the edge of the target, however. The same characteristics could be predicted by the integral of luminance close to the edge (see Figure 36) or by the integral of the logarithm of luminance close to the edge (see Figure 37). In both of these cases, though, the differences in the data between the results for the Sine targets and the results for the edged targets is greater than that predicted by the data. A surprisingly good fit to the data is obtained using the results of the convolution of the stimulus functions with the neural spread function of Campbell et. al.
(1969). Assume that a process occurs in visual processing which can be described by such a convolution. Secondly, assume that target edge information is represented by the integral over 4' of visual angle for the part of the convolution result which corresponds to the 4' area inside the edge of the target. This integral for each target stimulus was obtained and then normalized with respect to the largest of the four values. These values are graphed in Figure 41. The values fit the data quite well. Perhaps this model describes the profile of the positive, target side of a hypothesized, asymmetric edge detector (Shapley & Tolhurst, 1973).

This model seems to work, however, only for the results of the various targets not the Batman mask. The results for the Gate mask (see Figure 35c) for observer 2 are similar to the Batman mask results but this is not true for observer 1. The data for observer 1 for the Gate mask, however, resemble the integral over 2' instead of 4' of visual angle except that the differences between the Sine stimuli and the edge stimuli are smaller than that predicted by the model. Other characteristics of the Gate mask data for observer 1 are described by the model, though: Sine R target was masked more than the Sine A target while Batman target was masked more than the Gate target. It is possible that the change in observer 1's data occurs because the area over which the integral is taken is a function of mask edge gradient. The assumption would have to be made,
Fig. 41. Comparison of the data with the convolution of the line spread function (Campbell, Carpenter & Levinson, 1969) and the stimulus functions over 4' of visual angle within each target for the Batman mask. Observer 1, •--•; observer 2, ▲--▲. Masks are described in Figure 36.

however, that observer 1 was not affected in the same way. Nonetheless, it is interesting that this model fits any of the data. The most likely interpretation of this fit, (other than a chance result) is that the similarity between amount of masking and the convolved function of target luminance is that in some way the target inhibits itself. Perhaps the function of the mask is to switch some processing link such that this self-inhibition can occur.

Whatever the precise function of the target edge and mask edge information, the data clearly show that metacontrast depends on the interaction of the target and mask edge information. These two sources of information are treated differently
in visual processing as far as masking is concerned. One possible interpretation is that the mask edge information is treated as a function of weighted luminance while the target edge information is treated in visual processing as a function of luminance convolved with a neural spread function. This suggestion is consistent with the hypothesis that the mask undergoes only incomplete processing before it is able to interfere with the processing of the target. One way in which this interference could occur is that the mask edge information could ready the target processing system such that the target edge information would null the target information about the target. A second possibility is that metacontrast is a function of the output of asymmetric edge detectors (Shapley & Tolhurst, 1973), a suggestion which is qualitatively supported by the data of this experiment.

Temporal Effects as a Function of Luminance Gradients

The lateral inhibition hypothesis predicts that for a given target, a mask with more luminance at its edge will produce a more rapid change in graded neural potentials resulting in a faster rise time for the inhibitory component. This increase in rise time predicts a shift of the ISI at which the greatest amount of masking occurs to longer ISIs for the mask with more edge luminance. The incompletely-processed-mask hypothesis predicts that for a given target, the mask with a more completely formed edge will enter more rapidly into
processing, yielding a faster rise time for the corresponding neural component. This hypothesis also predicts a shift of the ISI at which greatest amount of masking occurs to longer ISIs for the mask with more edge luminance.

The temporal data are not consistent with these hypotheses. The temporal results for a given mask were averaged across targets for the ISI at which the greatest amount of masking occurred for that target-mask combination at a separation of 1'. These results are shown in Figure 42. The only trend of a shift of the ISI at which the greatest amount of masking occurs to longer ISIs with increased mask edge gradients occurs for the increase in mask edge luminance from the Sine R to the Sine A masks. Otherwise, the temporal characteristics of the data show a shift to shorter ISIs for increased mask edge luminance. This is entirely true for observer 2. Observer 1 shows no change in ISI for which the greatest amount of masking occurs for the Gate and Batman masks. The differences in ISI for which the greatest amount of masking occurred for different masks is a statistically significant one (Mask X ISI interaction).

The two temporal hypotheses can also be evaluated by considering the effects of targets with different edge gradients for a constant mask. The lateral inhibition model would predict that a target with less edge luminance would correspond to an excitatory component which would rise more slowly than would the component corresponding to a target with a greater amount of edge luminance. A similar argument can be made for the
Fig. 42. ISIs in milliseconds at which the greatest amount of masking occurred for each mask, averaged across targets. Observer 1, o—o; and observer 2, Δ--Δ. The masks are described in Figure 36.

Incompletely-processed-mask hypothesis. In each case, to obtain maximum masking, the effect of the mask would have to be shifted to longer ISIs for targets with decreased edge luminance. The target with less edge luminance will correspond to a more slowly rising excitatory component. A given mask will have its maximum effect at a longer ISI for such a target as compared to a target with greater edge luminance.

The temporal results for a given target were averaged across the different masks for the ISI at which the greatest amount of masking occurred for that target-mask combination at a separation of 1'. These results are shown in Figure 43. The data do not support either hypothesis. The data for observer 1 shows the predicted shift from longer to shorter ISIs as
Fig. 43. ISIs in milliseconds at which the greatest amount of masking occurred for each target, averaged across masks. Observer 1, o—o; and observer 2, Δ—Δ. The masks are described in Figure 36.

target edge luminance increases from the Sine R target to the Sine A target. However, there are no differences in average ISI at which peak masking occurred between the Sine A target and the Gate target. The results for the Batman target represent a shift to longer ISIs, contrary to the predictions of the hypotheses. The results for observer 2 show a shift to shorter ISIs for increasing target edge luminance in accord with the hypotheses for the Sine R, Sine A and Gate stimuli. However, the shift is in the opposite direction, to longer ISIs, for the increase in target edge luminance from the Gate to the Batman target. The differences in ISI for which the greatest amount of masking occurred for different targets is a statistically significant one (Target X ISI interaction).
Neither the lateral inhibition hypothesis nor the incompletely-processed-mask hypothesis are clearly supported by the data. This is true whether the results for different masks for a given target or the results for different targets for a given mask are considered. The temporal shifts in ISI at which the greatest amount of masking occurs are most likely a function of a more complex processing. Metacontrast depends on the interaction of target and mask edge information. It is quite possible that the temporal shifts which do occur are likewise a function of such interaction. This interpretation is supported by the statistical significance of the target X Mask X ISI interaction.

A different test of the lateral inhibition hypothesis is that of a temporal shift of the ISI at which the greatest amount of masking occurs as the distance from the mask to the target increases. As target-mask separation increases, the rise time of the inhibitory component should be decreased because of the distance which the hypothesized inhibition must travel to effect the target. The ISI at which the greatest amount of masking occurs, then, should shift to shorter ISIs as distance increases. The data do not support this hypothesis at all. In fact, if there is any shift, it is to longer ISIs as distance increases. This is true whether the target or mask data are considered. Table 12 shows the ISIs at which the greatest amount of masking occurs for each target for the first three target-mask separations. These results are averaged across masks for each
ISIs in milliseconds at which the greatest amount of masking occurred for the first three target-mask separations in minutes of visual angle for observer 1, 01, and observer 2, 02. The temporal results are averaged across masks for each target.

<table>
<thead>
<tr>
<th>Targets</th>
<th>Separation</th>
<th>(1')</th>
<th>(4')</th>
<th>(12')</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine R</td>
<td>01</td>
<td>90</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>95</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Sine A</td>
<td>01</td>
<td>65</td>
<td>75</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>85</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>Gate</td>
<td>01</td>
<td>65</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>65</td>
<td>75</td>
<td>65</td>
</tr>
<tr>
<td>Batman</td>
<td>01</td>
<td>75</td>
<td>95</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>75</td>
<td>95</td>
<td>100</td>
</tr>
</tbody>
</table>

Nearly every temporal shift is from shorter to longer ISIs. The same is true when the mask data are considered. Table 13 shows the ISIs at which the greatest amount of masking occurs for each mask for the first three target-mask separations. The results are averaged across targets for each mask. In both cases, for the target and the mask data, the shift is in the opposite direction to that predicted by the lateral inhibition model. If the lateral inhibition effect is to be found, it should be evident at least within the range where masking
Table 13

ISIs in milliseconds at which the greatest amount of masking occurred for the first three target-mask separations in minutes of visual angle for observer 1, 01, and observer 2, 02. The temporal results are averaged across targets for each mask.

<table>
<thead>
<tr>
<th>Masks</th>
<th>Separation</th>
<th>1'</th>
<th>4'</th>
<th>12'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine R</td>
<td>01</td>
<td>30</td>
<td>85</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>95</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>Sine A</td>
<td>01</td>
<td>85</td>
<td>85</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>90</td>
<td>90</td>
<td>110</td>
</tr>
<tr>
<td>Gate</td>
<td>01</td>
<td>60</td>
<td>70</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>70</td>
<td>85</td>
<td>90</td>
</tr>
<tr>
<td>Batman</td>
<td>01</td>
<td>70</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>80</td>
<td>90</td>
<td>80</td>
</tr>
</tbody>
</table>

Effects are significant. Secondly, if the weighting function of luminance for a particular target describes the significant aspect of mask edge information, then the lateral inhibition effect should show up within the range of these weights, the first 10' of target-mask separation. However, the data do not support the hypothesis that the effects of the mask on the target resemble the effects of a lateral inhibitory mechanism.
CHAPTER V

RESULTS REGARDING A SPATIAL FREQUENCY ANALYSIS IN
METACONTRAST

The stimuli which were used to test the hypothesis that
the phenomenon of metacontrast is, in part, a function of the
spatial frequencies of stimuli consisted of two targets (a
Gate and a Five c/d modulated Gate) and five masks (Gate, and
four sinusoidally modulated Gates of 2.5, 5.0, 10.0 and 15.0
c/d). A four-way analysis of variance (target X mask X separa­
tion X ISI) was performed on the brightness ratings of each
observer individually for these stimuli. The same statistical
model was used for the analysis as was described in Chapter IV.
The statistical results will be discussed where pertinent in
the following analysis.

General Characteristics of the Data

The data for the two observers are shown in Figures 44 to
53. As for previous figures describing the data, each graph
represents the data of an observer for a particular target­
mask combination. Each line within a graph represents the data
for a particular target-mask separation. Each point in each
graph represents the geometric mean over eight replications.
The graph of the data of observer 1 for a particular target­
mask combination is on the left; the corresponding graph for
observer 2 is always on the right. The first five graphs

168
depict the results for the Gate target with the Gate mask (Figure 44, identical to Figure 31 in Chapter IV), the 2.5 mask (Figure 45), the 5.0 mask (Figure 46), the 10.0 mask (Figure 47) and the 15.0 mask (Figure 48). The second set of five graphs depict the results for the 5.0 target with the same five masks in identical order (Figures 49 through 53).

The data for this part of the experiment possess characteristics which are quite similar to data obtained with non-modulated targets and masks. Masking varies as a function of ISI such that most masking is obtained at nonzero ISIs between 40 and 80 msec. for both observers. This is clear in the U-shaped functions of Figures 44 through 53. The amount of masking obtained at these ISIs, however, clearly depends on the spatial separation between target and mask. Most masking is obtained when the target and mask are close together. Masking drops off rapidly with distance and is usually zero by a separation of 43' for observer 1 and 84' for observer 2. This large difference in spatial extent of masking between the data for the two observers could be due, in part, to criteria differences between the observers. Observer 2, generally, gave smaller magnitude estimations (indicating greater amount of masking) than did observer 1. Both of the above effects, the main effects of ISI and of separation, are statistically significant (p < .01).

The amount of masking obtained with different masks
Fig. 44. Magnitude estimations of the Gate target with the Gate mask as a function of temporal interstimulus interval (ISI). Each line displays the results for one of the six spatial separations of target and mask: 1, O; 4', Δ; 12', +; 24', X; 48', Φ; and 84', Φ. The results for observer 1 are shown on the left; the results for observer 2 are on the right.
Fig. 45. Magnitude estimations of the Gate target with the 2.5 c/d mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 44.
Fig. 46. Magnitude estimations of the Gate target with the 5 c/d mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 44.
Fig. 47. Magnitude estimations of the Gate target with the 10 c/d mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 44.
Fig. 43. Magnitude estimations of the Gate target with the 15 c/d mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 44.
Fig. 49. Magnitude estimations of the 5 c/d target with the Gate mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 44.
Fig. 50. Magnitude estimations of the 5 c/d target with the 2.5 c/d mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 44.
Fig. 51. Magnitude estimations of the 5 c/d target with the 5 c/d mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 44.
Fig. 52. Magnitude estimations of the 5 c/d target with the 10 c/d mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 44.
Fig. 53. Magnitude estimations of the 5 c/d target with the 15 c/d mask as a function of temporal interstimulus interval (ISI). Other details as in Figure 44.
varied significantly (main effect of mask, \( p < .01 \)). Figure 54a depicts the peak masking values which were obtained for each target-mask combination at a separation of 1'. In Figure 54b, these peak masking values have been inverted (subtracted from 10, the number representing zero masking) and normalized with respect to the peak masking point for the data of both targets together. For observer 1, this point was for the Gate target—5 c/d mask; for observer 2, the maximum peak masking point was for the 5 c/d target—5 c/d mask. This procedure yielded a more representative description of the relative results of both observers; it corrected for a baseline (criteria) difference whereby an observer may give consistently larger or consistently smaller estimation numbers. The data are shown within a range of \( \pm 1 \) standard error. These standard errors were computed in the same manner as described in Chapter IV. They are of about the same magnitude as were the standard errors for the edge gradient stimuli. For observer 1, all standard errors are 11 percent or less except for two cases. The standard errors for the Gate target with the Gate mask and the 5 c/d mask are 17 percent. For observer 2, the standard errors are roughly similar, ranging from 8 to 13 percent. Generally, the Gate and 15 c/d masks were less effective than the masks of the middle frequencies, although this is not true for the data of observer 1 for the Gate target. Some of the curves in Figure 54, particularly for the 5 c/d target, resemble
Fig. 54. (a) Peak magnitude estimations for each target-mask combination at a separation of 1' for the data of the two observers. Observer 1, ○—○, and observer 2, △—△. 10 means no masking; a zero means complete occlusion of the target. (b) Same as above except that the data are inverted and normalized. A 1.0 means complete masking; 0 means no masking. Standard errors of ±1 are shown. The graph of the data of observer 2 is slightly offset.
contrast sensitivity functions for the visual system at threshold (e.g., Campbell & Robson, 1963) or describing functions for suprathreshold vision (Davidson, 1968). The resemblance is of interest because most masking is obtained for the same middle range of frequencies for which the visual system is most sensitive. Whether the amount of masking is related in a direct manner to the sensitivity characteristics of the visual system or to a frequency interaction as hypothesized will be discussed later.

The amount of masking also varies in a significant way for the two targets (main effect of target, \( p < .01 \)). In Figure 54b for observer 1, for example, the Gate target is almost equally well masked by the 2.5, 5.0, 10.0 and 15.0 c/d masks. For the 5 c/d target, however, the curve of peak masking values is sharply tuned about the 2.5 c/d mask. For observer 2, the differences between the results of the target are even more evident. Observer 2 shows least amount of masking of the Gate target for the 5 c/d mask with all other masks yielding more masking. For the 5 c/d target, most masking is obtained with the 5 c/d mask and least masking is obtained with the Gate mask. For both observers, the two targets are affected differently by the masks (target \( \times \) mask interaction, \( p < .01 \)). For observer 1 there is the difference in narrowness of tuning for the two targets and the shift in peak masking from the 5 c/d for the Gate target to the 2.5 c/d mask for the 5 c/d target.

In the data of observer 1, the masking values for the Gate
target are in the opposite direction to those for the 5 c/d target for the different masks. In particular, the Gate mask and the 2.5 c/d mask are much less effective for the 5 c/d target than they are for the Gate target; the 5 c/d mask, on the other hand, is more effective for the 5 c/d target than it is for the Gate target.

The manner in which the target and mask interact also changes as a function of separation (target X mask X separation interaction, p < .01). To some extent these effects may be due to the increased effectiveness of some masks over others. As separation increases, for example, for the 5 c/d mask, masking is obtained out to 34' for both observers (see Figure 51) for the 5 c/d target. For the Gate mask which is clearly less effective at a separation of 1' as compared to the 5 c/d mask (see Figure 54), masking of the 5 c/d target drops off almost to zero by 24' for observer 1 and by 48' for observer 2 (see Figure 49). This effect of rapid decrease in masking with increased separation for the 5 c/d target with the Gate mask is rather unique. It is an effect which is easily observed in the data of both observers and does not occur for other target-mask combinations.

It is clear that the two observers differ in their responses to the Gate target for the various masks. Observer 2 shows rather constant masking effects for the Gate target regardless of frequency mask. Observer 1, however, shows marked
differences depending on mask; in fact, his data resembles the data of observer 2 for the 5 c/d target. It is not evident why the two observers should differ in this manner. It seems unlikely that they are using different criteria since their results for the edge gradient stimuli are so alike; both the edge gradient and spatial frequency stimuli were presented in the same random order. From the model-building point of view, it would be preferable to find an explanation in terms of simple quantitative differences in parameters for identical information processing mechanisms.

Comparison of the Masking Amplitudes of the Edge Gradient and Frequency Stimuli

For both observers, the most effective combination of target and mask stimuli was the Gate target with the Batman mask. The relationship between the masking amplitudes of the edge gradient stimuli and the frequency stimuli can be seen more clearly if the data are normalized with respect to the masking result for the Gate target–Batman mask combination. These data are shown in Table 14 (compare to Table 8 in Chapter IV). In the data of observer 1, the Gate target is masked by the non-zero frequency masks almost as well as by Batman. This is not true in the data of observer 2 where all of the frequency masks are as effective or less effective than the Gate mask on the Gate target. The Gate target was masked to a greater extent than the Batman target for observer 1 for the Batman mask and
for observer 2 for the Gate and Batman targets. The masking obtained for the Batman target--Gate mask combination for observer 1 was equal to the masking for the 5 c/d target--2.5 c/d mask and the 5 c/d target--5 c/d mask. The masking obtained for the Batman target--Gate mask combination for observer 2 was equal to the masking for the 5 c/d target--5 c/d mask, and the 5 c/d target--10 c/d mask.

Comparison of the Frequency Data to Models of Edge Activity in Metacontrast

The increased effectiveness of masks in the middle range of frequencies, such as the 2.5 c/d and the 5 c/d masks (except for the data of observer 1 for the Gate target), can be accounted for in several ways. One important factor is that the masks differ in the amount of luminance at their edge. The 2.5 c/d mask, for example, has more luminance at its edge than any other mask. It is possible that the amount of masking obtained with each mask is related in a direct way to the amount of luminance at its edge. To test this hypothesis, the formulae describing the stimuli (stimulus intensity with respect to distance) were integrated over various limits measured from the edge of the mask. The limits which were selected were 2', 3', 4', 6', and 12' of visual angle. The resulting areas, representing amount of stimulus intensity near the edge of a particular mask within some limit, were normalized with respect to the largest of the five areas for that particular integration
limit. These normalized areas are presented in Figure 55. The only curve which possesses characteristics similar to any of the data is the integration of area over 2' of visual angle near the edge of the mask. This curve is similar to the results for observer 1 for the 5 c/d target. These two curves are compared in Figure 56. The curve representing area within 2' of the edge of the mask has been displaced vertically. The correspondence between model and data is everywhere within ±1 standard error. There is no a priori reason to assume that an integral over 2' of visual angle should resemble the data as opposed to integration over some other limit. It is possible, though, that this value is related in some way to the weighting function for a 5 c/d target. This weighting function is unknown but would probably be unique to the 5 c/d target (cf., Chapter IV). However, the model does not fit the data obtained from observer 2. Rather than accept the hypothesis that the amount of luminance near the edge might help explain the data for one observer but not the data for the other, it would seem more productive to search for a single model with characteristics such that adjustments in simple quantitative parameters would allow a fit to the data of both observers. The amount of mask luminance near the edge of the target does not possess these characteristics; nonetheless, the goodness of the correspondence cannot be disregarded.

A second possibility to explain the effectiveness of
Fig. 55. Normalized areas describing the amount of luminance within x minutes of the edge of the stimulus for several values of x. x = 2', o—o; 3', △—△; 4', □—□; 6', ●—●; and 12', ▲—▲.

Fig. 56. Comparison of the data of observer 2 for the 5 c/d target with the amount of luminance with 2' of the edge of the mask. The curve describing luminance has been displaced vertically. Observer 2, o—o. Amount of luminance, □—□.
masks in the middle range of frequencies is that masking is related, not to luminance near the edge of the mask, but to weighted luminance near the edge of the mask. This model is of particular interest because the masking of a Gate target with masks varying in edge gradient could be accounted for in part by weighted mask luminance near the edge of the target for both observers (see Chapter IV). To test this model, the weighting function described in Chapter IV was convolved with each of the stimulus functions which specify the frequency stimuli. The functions were convolved over several limits of integration: 2', 3', 4', 5', 6', 8', and 11' of visual angle. The results of the convolution for the five stimulus functions were normalized with respect to the largest of the five areas for that particular integration limit. Some of these normalized values are displayed in Figure 57a. On the assumption that the weighting function used both here and in Chapter IV is specific to the Gate target (see Chapter IV), one set of the normalized values should fit the data for one or both of the observers for the Gate target. It is clear, however, from comparing Figure 57 with the data of the Gate target for either observer in Figure 54, that the fit of the model to the data is poor. No vertical displacement of any of the sets of normalized values will come close to approximating the data characteristics. For observer 2, the Gate target is masked more by the Gate mask than is predicted by the model; for both observers, the 10 c/d
and 15 c/d masks are more effective than predicted by the model. It is of some interest that the normalized values representing integration over 3' of visual angle approximate the data of observer 1 for the 5 c/d target if the set of normalized values are displaced vertically (Figure 57b). The correspondence between model and data is everywhere within ±1 standard error. However, this correspondence is obtained by integrating over 3' of visual angle in the model. A different limiting condition, 4' of visual angle, was used to match the data of observer 1 for the Gate target with edge gradient stimuli (see Chapter IV). Further, none of the models of weighted luminance approximate the data of observer 1 for the 5 c/d target. Because the data of only one of the observers correspond to the model and because the model corresponds to the data for the 5 c/d target (which is not consistent with the assumption that the weighting function is target specific), it is concluded that the data obtained with the frequency stimuli are not accounted for by a weighted luminance model based on Growney and Weisstein (1972).

There is one correspondence between weighted luminance and the masking data which is interesting but difficult to interpret. Shapley and Tolhurst (1973) graphed the spatial frequency transform of the sensitivity results which they attribute to an antisymmetric edge detector (their Figure 6). Because of the close similarity of their sensitivity results to the weighting function determined by Growney and Weisstein
Fig. 57. (a) Normalized areas describing the amount of weighted luminance within x minutes of the edge of the stimulus. x = 2', ○—○; 3', △—△; 4', □—□; 3', ×—×; and 11', ▲—▲. (b) Comparison of the data of observer 1 for the 5 c/d target with the amount of weighted luminance within 3' of the edge of the mask. The curve describing weighted luminance has been displaced vertically. Observer 2, ○—○. Amount of weighted luminance, △—▲.
Table 14

Peak masking data for the frequency stimuli, normalized with respect to the datum of each observer, O1 and O2, for the Gate target-Batman mask combination of stimuli.

<table>
<thead>
<tr>
<th>Masks</th>
<th>Gate</th>
<th>2.5 c/d</th>
<th>5 c/d</th>
<th>10 c/d</th>
<th>15 c/d</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gate Target</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O1</td>
<td>0.57</td>
<td>0.37</td>
<td>0.94</td>
<td>0.93</td>
<td>0.34</td>
</tr>
<tr>
<td>O2</td>
<td>0.34</td>
<td>0.32</td>
<td>0.72</td>
<td>0.78</td>
<td>0.31</td>
</tr>
<tr>
<td><strong>5 c/d Target</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O1</td>
<td>0.34</td>
<td>0.74</td>
<td>0.63</td>
<td>0.47</td>
<td>0.21</td>
</tr>
<tr>
<td>O2</td>
<td>0.41</td>
<td>0.69</td>
<td>0.34</td>
<td>0.78</td>
<td>0.71</td>
</tr>
</tbody>
</table>

(1972), this transform also describes the frequency response corresponding to the weighting function for the Gate target. However, as described above for the convolution of the weighting function with the frequency stimuli, the spatial frequency transform of the edge detector, which peaks at 3 c/d, follows very closely the masking data of observer 1 for the 5 c/d target, which peak for the 2.5 c/d mask. The general characteristics of the two functions are quite similar. Again, there is the discrepancy that the theoretical curve matches the data of observer 1 for the 5 c/d target, instead of for the Gate target, on the basis of which the weights were calculated. Ignoring this point for the moment, it is interesting that the spatial frequency transform for the sensitivity of a second observer in Shapley and Tolhurst's study peaked at 5 c/d. The
data of observer 2 for the 5 c/d target also peak for the 5 c/d mask. Although Shapley and Tolhurst do not mention the other characteristics of the spatial frequency transform for the sensitivity of their second observer, the shift of the spatial frequency transform to 5 c/d is consistent with a narrower sensitivity (or weighting function) profile. A narrower weighting function for the data of observer 2 would predict the greater effectiveness of the higher frequency-modulated masks for observer 2 as compared to observer 1. This correspondence between the peak of the transform for Shapley and Tolhurst's second observer and the peak of the masking function for observer 2 suggests that the differences between the two observers of this study may be due to individual weighting function differences. The magnitude of the peak differences in the spatial frequency transforms of the sensitivity profiles for the observers in Shapley and Tolhurst's study are, at least, of the same order as the peak differences in the masking functions for the two observers in this study.

The correspondence between the spatial frequency transform of the edge detector and the masking data obtained with the sinusoidally-modulated stimuli is difficult to interpret. It is not clear why the amount of masking obtained with a particular mask modulating frequency should correspond to the amount of that same frequency in the spatial transform of the edge detector function. It would be surprising if hypothesized frequency channels in the visual system were weighted in proportion
to the spatial frequencies corresponding to the edge detector function. There is, at least, no direct relation between weighted luminance and the masking data with the sinusoidally-modulated stimuli. If this were the case, some model of weighted luminance should have corresponded to the data. It is necessary to conclude that factors other than the hypothesized edge detector are operative in metacontrast.

The Effects of the Transfer Characteristics of the Optics of the Eye

The comparison of the data to models of luminance or of weighted luminance might be complicated by the transfer characteristics of the optics of the eye. The optics of the eye sharply attenuate higher spatial frequencies (Westheimer & Campbell, 1962; Campbell & Gubisch, 1966). Gain decreases rapidly with frequency (see Figure 15 in Chapter III). Perhaps the attenuation due to the optics of the eye decreases the effectiveness of mask luminance at the edge of higher frequency masks as compared to lower frequency masks. If metacontrast is a function of an edge mechanism, the edge mechanism might receive less input from higher frequency masks. Less masking might then be predicted. Because most masking was obtained for the middle range of frequencies but not zero frequency, however, the reduced effectiveness of the higher frequency masks is not directly related to this optical attenuation. If a direct relation were the case, masking should have been a decreasing
function of frequency. Even if the data were corrected for the characteristics of the optics of the eye, the correction would be in the opposite direction to that needed to fit the models to the data. For the Gate target for both observers (see Figure 54), the models already predict too little masking for the 5 c/d, 10 c/d, and 15 c/d masks. Taking into account the attenuation of the higher frequencies due to the optics of the eye would only lead to the prediction that even less masking should have been obtained than was predicted by the original models. For the 5 c/d target for the data of observer 2 where the luminance model fits best, correction for the eye optics would only lead to a poorer fit of model to data.

These results suggest that the masking which was obtained with the frequency stimuli is due to other factors than simply mask luminance near the edge of the target or to weighted mask luminance near the edge of the target. This conclusion seems especially important because the weighted luminance model predicted fairly well for both observers the masking effects for a Gate target with masks which had sharp edges (see Chapter IV and the discussion of Shapley & Tolhurst's [1973] hypothesis earlier in this Chapter). The masking effects for this same Gate target with frequency-modulated masks, however, are not predicted at all. Other mechanisms, then, seem to be involved in the masking effect.
Correspondence of the Data to Models of Spatial Frequency Interaction

Because of the limitations on luminance in the tachistoscope, the stimuli could not be corrected in a useful manner (see Chapter III). The strategy which will be followed in order to test models of spatial frequency interaction will be to correct the data instead. In order to know what changes in an observer's magnitude estimation responses should be made for a hypothesized change in mask luminance, it is necessary to (1) know how changes in mask luminance affect target luminance in a masking situation, and (2) know how changes in target luminance affect the magnitude estimation responses of the observer. An approximation to (1) can be obtained from Alpern (1953). In one experimental condition Alpern observed changes in target luminance, TL, as a function of mask luminance, ML. For an 11 ft.L. comparison stimulus, the relation between target and mask luminance, obtained by a graphical approximation, is given by

\[ \log (TL) = \log (19.06) + (0.416) \log (ML). \]

This relationship holds for mask luminance over the range from about zero ft.L. to 100 ft.L.

The relation between the magnitude estimations, M.E., of the observer and target luminance, (2), was obtained for each observer as described in Chapter III. The general form of this relation is
\[
\log (\text{M.E.}) = \log (K) + n \log (\text{TL})
\]

where \(K\) and \(n\) are specified for each observer over a limited range of target luminance. It will be assumed that this limited range for target luminance applies identically to mask luminance. The relation between magnitude estimation and mask luminance can then be obtained by substitution for \(\log (\text{TL})\) such that

\[
\log (\text{M.E.}) = \log (K) + n [\log (19.06) + (0.416) \log (ML)]
\]

or

\[
\log (\text{M.E.}) = \log (K) + n \log (19.06) + n (0.416) \log (ML)
\]

A major point of this relationship between magnitude estimation and mask luminance is that changes in mask luminance are shown to have a reduced effect on magnitude estimation because of the exponent for mask luminance of 0.416 which is less than unity.

Suppose now that the mask stimuli had been multiplied by a correction coefficient, \(C'\). The corrected magnitude estimation corresponding to this changed mask luminance would have been

\[
\log (\text{M.E.})_c = \log (K) + n \log (19.06) + n (0.416) \log (C' \cdot ML)
\]

or

\[
\log (\text{M.E.})_c = \log (K) + n \log (19.06) + n (0.416) \log (C') + n (0.416) \log (ML).
\]

The only difference in this equation as compared to the uncorrected equation is the term, \(C = n (0.416) \log (C')\). It follows that
To correct the data, then, the data were first inverted by subtracting the observer's magnitude estimation response from 10. Because of this inversion, larger magnitude estimation numbers correspond to more masking and smaller numbers correspond to less masking. The correction factor, C, was then added to the logarithm of the inverted data. This method of correcting the data is only an approximate procedure. It is unknown how the relationship between target luminance and mask luminance changes for individual observers or for stimuli which differ from the Gate stimuli used by Alpern. At best, such factors make any conclusion based on an analysis of the corrected data only tenuous although suggestive for further research.

The value of mask luminance to be used in the relation between magnitude estimation responses and mask luminance is the amplitude of the stimulus function. The correction factor represents the reciprocal of the composite effects of the transfer characteristics of some initial stages of visual processing. The whole idea of the correction factor is to counterbalance the effects of these stages as they change the magnitude estimation response of the observer. Because the transfer characteristics of these stages are measured in terms of normalized gain which is related to the amplitude of frequency components, the correction factor, C, which is related to the reciprocal of
normalized Gain, should be applied to the amplitude of the stimulus function. This factor is important because the product, $C' \times ML$, determines which value of the exponent, $n$, is relevant for the correction factor for the data of a particular observer (see Chapter III). Use of the amplitude of the stimulus luminance function means that the smallest value of $n$ will be used for most data corrections. The effect of small $n$ is to make the correction factor, $C$, smaller so that the data are not changed drastically by the correction factor. This diminished effect of the correction factor is consistent with the small differences in brightness ratings for stimuli with different modulating frequencies (see Chapter III).

To guide the decision as to what corrections should be made to test models of spatial frequency interaction, three different models of information processing will be assumed to account for masking effects in the visual system. The data will first be corrected based on the particular information processing model. Models of spatial frequency interaction will then be compared to the corrected data.

For the first model of information processing for meta-contrast, it will be assumed that targets and masks with internal contours undergo a different processing than do stimuli without such contours. To distinguish this situation from a masking situation involving Batman as a stimulus, for example, internal contours will be defined as an internal decrease to the level of the background luminance. Only the
frequency-modulated stimuli had such a decrease. Masking which is due to such stimuli may be a result primarily of a different kind of processing. In particular, such processing may involve the spatial frequency components corresponding to the stimuli, on the assumption that a preprocessing similar to a Fourier analysis occurs in the visual system and is relevant to suprathreshold processes. For this model, then, the stages of information processing are (1) optical transfer characteristics of the eye, (2) Fourier analysis of the neural code corresponding to the stimulus, and (3) some activity involving the results of the Fourier analysis which yields masking as output. Various models of this, as yet, unspecified activity will be compared to the data.

To make this comparison, the data should be corrected for the transfer characteristics of the optics of the eye. The corrective coefficient for mask luminance, $C'$, for a particular spatial frequency is the reciprocal, $1/(\text{normalized Gain})$, of the ordinate of the curve displayed in Figure 15 of Chapter III corresponding to the given frequency. Strictly speaking, the reciprocal, $1/(\text{normalized Gain})$, should only be applied to a periodic function corresponding to the given frequency. When such a correction factor is applied to the aperiodic stimuli of this study, however, the frequency spectra are distorted. For example, to apply the correction factor for a grating of 10 c/d to the aperiodic 10 c/d modulated Gate mask, other frequencies in the mask transform, such as at 5 c/d, are
disproportionately amplified. For this reason, the data were not corrected for the transfer characteristics of the eye optics.

However, consider the following argument. The comparisons of model to data which follow are made for the normalized areas either between masks or between target and masks. These comparisons will be made over limited bandwidths of frequency on the assumption that a single channel or independent channels filter or select frequencies at some stage of processing. If the optical transfer function or even the combined transfer function for the optics and neural characteristics of the visual system are treated as a constant within these bandwidths, then the constants describing these transfer characteristics drop out in the normalization process. The comparison of all masks or the comparison of the target to the five masks is always made within the same bandwidth for all stimuli; the constant describing the transfer characteristics of the two filters are always, therefore, the same.

For comparison of data to spatial frequency models of limited bandwidth, then, two versions of this first model of information processing are indistinguishable for present purposes. Prior to the hypothesized Fourier analysis, visual input may be subject to only the transfer characteristics of the eye optics or to both the transfer characteristics of the eye optics and to neural transfer characteristics, as described, for example, by Patel (1966). The uncorrected data will be
representative for either version.

For the second model of information processing for meta-contrast, it will be assumed that two masking mechanisms are involved. The hypothesis is that the masking effects will be due to the combined operation of both mechanisms. Depending on the kind of stimulus, the masking effects may be due primarily to one or the other of the mechanisms. Specifically, the following stages of processing are hypothesized: (1) the optical transfer characteristics of the eye, (2) a uniform attenuation (uniform with respect to space) of the neural code corresponding to the target stimulus which is proportional to the weighted mask luminance near the edge of the target (as in Chapter IV), (3) a Fourier analysis of the neural code corresponding to the stimuli and (4) some activity involving the results of the Fourier analysis which yields masking as output.

In order to compare the data to models involving the results of a Fourier analysis (stage 4), it is necessary to correct the data for the weighted mask luminance near the edge of the target. The transfer characteristics of eye optics will again be assumed negligible for models of limited bandwidth. The correction coefficient, C, for weighted mask luminance for a particular frequency modulated mask is the reciprocal of the normalized area shown in Figure 57a. For observer 1, the set of normalized areas corresponding to weighted mask luminance within 4' of the target edge were used. The set of normalized areas for weighted mask luminance within 3' of the target edge
201

were used for observer 2. In both cases, these were the areas which came closest to accounting for the masking of a Gate target by masks varying in edge gradient. On the assumption that a weighting function is target-specific, these areas should also describe part of the masking effect of the Gate target with frequency modulated masks; that is, these areas should predict stage 2 activity. Because the weighting function for a 5 c/d target is not known, these same areas will be used for the 5 c/d target as the closest available approximation. For a particular mask, then, the correction factor, C, was added to the logarithm of the inverted data as explained above. The data, corrected for the transfer characteristics of weighted mask luminance near the edge of the target, are shown in Figure 53. The major difference in these data with respect to the uncorrected data is that the masks with lower and higher modulating frequencies are slightly more effective. For the data of observer 1 for the Gate target, for example, the most effective mask for corrected data is now the 10 c/d mask instead of the 5 c/d mask. Generally, the characteristics of the uncorrected and corrected data are the same.

One model of the use of spatial frequency information in metacontrast involves the following assumption. Assume that masking is related to the amplitude of the spatial frequency transform of the mask at some specific value of frequency. This model could not be a sufficient explanation of metacontrast since the effectiveness of a particular mask varies depending on the
Mask Modulation Frequency (In Degrees)

Fig. 58. Data corrected for the amount of weighted luminance within 4' of the stimulus edge for observer 1 and 3' of the stimulus edge for observer 2. The data are normalized across targets for each observer independently. Observer 1 \( \circ \); observer 2, \( \Delta \).

However, the model does not predict the data for either target. At zero frequency, for example, the magnitude of the frequency transform for each of the masks is the same, \( F(0) = 14.4 \), but the data show considerable variability in their effectiveness. At other selected frequencies the predictions are no better. Consider the modulating frequencies for the masks: 2.5, 5, 10, and 15 c/d. The frequency transforms of the masks are related such that only one of the masks has nonzero magnitude for one particular modulating frequency. For example, the 5 c/d mask has a magnitude of 7.2, one-half the magnitude of the transform at zero frequency,
for a frequency of 5 c/d. All other masks are zero at 5 c/d. On the other hand, the 10 c/d mask has an amplitude of 7.2 at 10 c/d whereas all other masks have a zero 10 c/d frequency component. If masking is related to the magnitude of a particular frequency component, this model would predict that the effectiveness of a mask with that critical masking frequency as its modulating frequency would be large compared to the effectiveness of masks with other modulating frequencies.

This same prediction also holds true if it is assumed that this hypothesized critical masking frequency is not one point but, instead, a small range of frequencies, that is, a channel with some small bandwidth. For this extension of the hypothesis, assume that masking is related to the magnitude of spatial frequencies that exist within the bandwidth for a particular mask. The frequency transform for each of the masks was integrated over two measures of bandwidth which are specified in Table 15. These limits represent the first zero and second zero of the frequency transform, that is, the first and second points, on either side of the hypothesized critical masking frequency where \( F(w) = 0 \). The resulting areas were normalized with respect to the largest of the five areas for a particular condition. For the condition of narrowest bandwidth, a mask whose modulating frequency is centered at the critical masking frequency has a very large component of spatial frequencies; masks whose modulating frequency are not centered at the critical masking frequency have very small areas. This
Table 15

Measures of channel bandwidth with frequency limits A and B in degrees for (a) a narrow channel, to first zero on either side of the center frequency, and (b) a wider channel to second zero on either side of the center frequency.

<table>
<thead>
<tr>
<th>Center Frequency</th>
<th>(a) Narrow</th>
<th>(b) Wider</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>2.5</td>
<td>1.25</td>
<td>3.74</td>
</tr>
<tr>
<td>5</td>
<td>3.74</td>
<td>6.23</td>
</tr>
<tr>
<td>10</td>
<td>8.73</td>
<td>11.4</td>
</tr>
<tr>
<td>15</td>
<td>13.7</td>
<td>16.2</td>
</tr>
</tbody>
</table>

The description is qualitatively similar to that of the magnitude of the frequency transform of the masks for the same selected frequencies of 2.5, 5, 10, and 15 c/d. It is clear from Figures 54b or 58 that no single mask is extremely effective in comparison to the other masks. It does not seem likely, therefore, that the effectiveness of a mask is directly related either to the magnitude of a particular frequency component or to the magnitude of frequencies within a single channel of narrow bandwidth. For slightly larger bandwidths, that is, to the second zero on either side of the center frequency, the predicted effectiveness of different masks become irregular and are not similar to the data. For example, the area for the Gate mask and the 10 c/d mask with a center frequency of 5 c/d are less than the area for the 5 c/d mask. However, the area for the 10 c/d mask is also smaller than the area for the 15 c/d mask.
mask. A graph of these areas describe an irregular sawtooth shape rather than the single peak shape of the data.

A slightly different model of mask effectiveness was suggested by the comparison of the contrast of the stimuli as discussed in Chapter III. This contrast function for the data of each observer was especially interesting because it resembles the general characteristics of the data of each observer for the 5 c/d target. This contrast function was normalized with respect to peak contrast and is shown with the data of each observer for the 5 c/d target in Figure 59. The data shown are the uncorrected data which correspond more closely to the contrast function than do the data corrected for the weighted mask luminance at the edge of the target. For both observers the correspondence of the contrast function to the data for the Gate mask is poor. The Gate mask has zero contrast but was a very effective masking stimulus. Of the data for the remaining four masks, the contrast function corresponds well to the data for three of the masks for each observer. More masking was obtained for the 15 c/d mask, 0.22, for observer 1 than are predicted by the contrast function, 0.12. The value, 0.12, lies just below minus one standard error, 0.14. For the data of observer 2, the contrast function for the 15 c/d mask lies just inside minus one standard error. However, for the 2.5 c/d mask, less masking was obtained, 0.83, than was predicted by the contrast function, 0.93. This point lies outside plus one standard error, 0.94.

Although the correspondence of the contrast function to
the data for each observer is good for only three of the five comparisons, the correspondence of the general characteristics of the contrast function to the data of each observer is very interesting. Such a result could be obtained on the assumption that a single channel mechanism evaluates the contrast of the masking stimulus and attenuates some characteristic of the neural code corresponding to the target in proportion to the masking stimulus contrast. Although the contrast function corresponds best to the amount of masking as a function of the different masking stimuli for the 5 c/d target, this result does not imply that masking is only a function of masking.

Fig. 59. Comparison of the uncorrected data to the contrast ratings of the masking stimuli. The contrast rating curves have been displaced vertically so that the peaks of the data and rating curves coincide. Standard error, ±1, is shown. Data: observer 1, ■—■; observer 2, ○—○. Contrast ratings: observer 1, •—•; observer 2, ◆——◆.
stimulus contrast. The contrast function corresponds only to the data for the 5 c/d target and does not fit the data for the Gate target. This means that masking is also a function of the target as corroborated by the statistical significance of the target-mask interaction. However, it is not clear whether the amount of masking of the same set of masks for some other frequency-modulated Gate target, such as a 2.5 c/d or 10 c/d target, would have been fit by the contrast function. This would imply that the masking is a function of the contrast of the masking stimuli only as long as the target is frequency-modulated also. This implies that the Gate target is processed in a different manner and is not processed as zero contrast. This observation is consistent with the masking results of the 5 c/d target by the Gate mask, and would be consistent with the statistical significance of the target-mask interaction. On the other hand, the contrast function may be target specific. The above contrast function was obtained using a 5 c/d stimulus as the modulus of 10. Masking data for a 2.5 c/d target might be well fit by a contrast function obtained with a 2.5 c/d stimulus as the modulus. In this way, masking would also be a joint function of the target and masking stimuli.

Because masking varies as a function of both mask and target (main effects of target and mask and the target X mask interaction), it is of interest to examine models in which the frequency spectra of both target and mask are considered.
One such model is to assume that amount of masking is related to the degree of similarity between the frequency spectra of target and mask. Similarity was measured by cross-correlating the frequency transform of the target, \( F_t(w) \), with the frequency transform of the mask, \( F_m(w) \), such that

\[
CC(w) = \int_{A}^{B} F_t(w) \times F_m(w - t) \, dw
\]

where \( t = 0 \), and \( A \) and \( B \) depend on particular conditions. A Riemann sum approximation was used with delta \( w = 0.01 \). This integral was obtained for each combination of target and mask at each of the six separations between target and mask for a variety of conditions.

As the first hypothesis using this model, assume that masking is directly related to the similarity between the frequency spectra of target and mask over the entire spectrum. For vision the range of frequencies which seems relevant to suprathreshold vision is approximately from zero to 25 c/d (e.g., Cornsweet, 1970). The frequency domain of contrast sensitivity curves for threshold vision extends out to 100 c/d (e.g., Campbell, Carpenter & Levinson, 1969). However, the differences in the frequency spectra of the stimuli are greatest within the range from 0 to 20 c/d. For this reason, attention was directed to this region of the frequency domain. The frequency spectra of target and mask were cross-correlated, then, over the domain from \( A = 0 \) to \( B = 25 \) c/d (\( w = 130 \)). The resulting
areas were normalized with respect to the largest of the ten areas (a set of five areas for both the Gate and 5 c/d target) for a particular separation. The results for a separation of 1' of visual angle are shown in Table 16. Over the whole frequency range, the low frequencies predominate in the correlation. Over all, the frequency transform of the Gate mask has more points (frequencies) in common with the frequency transform of either target than do the transforms of any of the other masks. This model does not fit the data, not even the data of observer 1 for the Gate target. However, because this comparison is being made over the whole visual spectrum of frequencies and not a limited bandwidth, the effects of the optical spread function must be taken into account. As was seen in Figure 15 in Chapter III, the effect of the optics of the eye is to attenuate higher frequencies. This means that major frequency components of the 10 c/d mask and the 15 c/d mask in particular would be diminished in amplitude. The net result of this attenuation would be an even smaller cross-correlation number for these higher frequency masks. This change is in the opposite direction needed to provide a better correspondence of the model to the data. This discrepancy between the model and data becomes more pronounced if the variable of separation between the target and mask is also considered. A marked decrease in amount of masking occurs with increased spatial separation between target and mask. The model, on the other hand, predicts very little decrease in amount of masking for increasing
Results of the cross-correlation of the frequency spectra of the target and mask at 1" separation over the frequency range from 0 to 25 c/d.

<table>
<thead>
<tr>
<th>Masks</th>
<th>0</th>
<th>2.5</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 c/d</td>
<td>1.00</td>
<td>0.505</td>
<td>0.504</td>
<td>0.503</td>
<td>0.502</td>
</tr>
<tr>
<td>5 c/d</td>
<td>1.00</td>
<td>0.513</td>
<td>0.544</td>
<td>0.506</td>
<td>0.504</td>
</tr>
</tbody>
</table>

separation. This discrepancy between the data and any of the frequency models is large.

A second hypothesis is based on the following assumption. Assume that masking is directly related to the similarity between the frequency spectra of target and mask over a restricted frequency domain. Masking might correspond to the similarity in frequency of target and mask as sampled by a channel with narrow bandwidth. In order to test this possibility, the frequency spectra of target and mask were cross-correlated over a domain specified by the limits for A and B shown in Table 15. The resulting areas were normalized with respect to the largest of the ten areas for a particular separation for a particular set of limits. The normalized areas for the 1" separation for the different sets of limits are shown in Figure 60 for both the Gate and 5 c/d targets. The predictions of the model differ for the two targets; this is to be expected because the frequency spectrum of the target was used in the cross-correlation. For
Fig. 60. Normalized areas describing the results of the cross-correlation of the frequency spectra of the target and mask for (a) narrow bandwidth (to the first zero on either side of the center frequency) and (b) wider bandwidth (to the second zero on either side of the center frequency) about several center frequencies. Center frequencies are 2.5 c/d, o—o; 5 c/d, △—△; 10 c/d, □—□; and 15 c/d, •—•.
the narrowest bandwidth (to the first point (first zero) on either side of the center frequency where \( F(w) = 0 \)), the cross-correlations peak for the mask whose modulating frequency is the same as the center frequency of the model (see Figure 60a). For example, when the center frequency is 15 c/d, the cross-correlation is greatest for the 15 c/d mask and much lower for all four of the other masks. In fact the peak area usually differs from the other areas by at least 50 percent. None of the curves describing the data (see Figures 54b or 53) show any such large differences between the results for one mask as compared to the other masks. Further, the model predicts that the same mask should be most effective for both targets. The data for both observers show clearly that different masks are most effective depending on the target.

The predictions of the model for a slightly wider bandwidth (to the second zero on either side of the center frequency) are shown in Figure 60b. The predictions for the 10 and 15 c/d center frequencies are similar to those for the narrower bandwidth condition. The model predicts that the mask whose modulating frequency is the same as its center frequency should be the most effective masking stimulus. The predictions for the 2.5 and 5 c/d center frequencies with wider bandwidth differ in this respect. For a 5 c/d center frequency, the model predicts the greatest amount of masking (peak masking) of the Gate target by the 2.5 c/d mask and the greatest amount of masking of the 5 c/d target by the 5 c/d mask. It is interesting
that the model predicts differential results for the two targets on the basis of the same center frequency. However, the predictions of the model do not correspond to the data. For the data of observer 1, for example, the corrected data for the Gate target peak at the 10 c/d mask; the corrected data for the 5 c/d target peak at the 2.5 c/d mask. This shift of peak masking with respect to the target does not correspond to the model and is also in the opposite direction to that predicted by the model. For a center frequency of 2.5 c/d, the model predictions of a peak shift are the same as for the 5 c/d center frequency. However, because the center frequency is so low, the cross-correlations are similar due to the low frequency similarity of the five masks. This prediction is of interest because the data of observer 2 for the Gate target show little differences in effectiveness between masks. However, the model does not predict the inversion found in the data of observer 2 where the least effective mask is the 5 c/d mask. On the other hand, the model does predict similar results for both targets; the data for observer 2 for both targets are qualitatively different. The model did predict the inversion, though, if the following change in the cross-correlation was made. Before cross-correlating the frequency spectra of target and mask, the spectrum of each stimulus was first normalized with respect to the maximum of the spectrum at F(0). After this normalization of frequency spectra was done, the entire cross-correlation
procedure was repeated for all targets and masks at the six target-mask separations. In all respects the predictions of the models using cross-correlation based on the normalized or non-normalized frequency spectra were qualitatively the same with one exception. With the center frequency at 2.5 c/d, the normalized model predicts least masking of the Gate or 5 c/d target by the 5 c/d mask. In this respect, the data of observer 2 are similar to the predictions of the model. The model, however, predicts a much greater difference between the effectiveness of the Gate mask and the 5 c/d mask. The model predicts a 63 percent difference whereas the data show less than a 15 percent difference. Finally, the model predicts that the 15 c/d mask for the Gate target should be only half as effective as the Gate mask. In the data, the 15 c/d mask is more effective than the Gate mask for observer 2.

One reason why the data of either observer for the two targets might differ is that a cross-correlation performed on the single channel filtered output of the stimulus frequency spectrum might predict target differences as occurred above for the cross-correlations of the normalized frequency spectra. A second possibility is that the data for the two targets differed, or the data for the two observers differed, because different criteria within the observers' processing system were adopted. A criterion shift within the visual system might mean a shift in the center frequency for a single channel
filter. The center frequencies which were selected, 2.5, 5, 10, and 15 c/d, constitute a fairly good sample of the domain of frequencies in the most sensitive region of the contrast sensitivity curve. None of the models based on these channels fit the data well.

Another possibility, however, is that the data are the output of a multi-channel system, not a single channel system. The comparison of the frequency spectra of target and mask might be performed subsequent to the filtering of the frequency spectra by several different channels each of which might be centered at a different frequency. The data might then correspond to the sum of the cross-correlations obtained by the individual channels. This possibility was not tested in a systematic manner; that is, not all combinations of cross-correlations were attempted. However, several representative combinations of cross-correlations for the single channel model described above were tried. For example, assume that the visual system has two channels, a low frequency and a high frequency channel. To test this idea, the cross-correlation output for a center frequency of 2.5 c/d and for a center frequency of 15 c/d were added together. This sum was also obtained for different linear weightings of the cross-correlation results with the 15 c/d center frequency. In all cases, the model would predict too sharp of a peak so that one mask would be much more effective than any other, or would predict several peaks, or would predict peak masking for masks which did not
correspond to the data. These combinations were also tried
with the 2.5 c/d and a 10 c/d center frequencies and for various
combinations of three channels, such as a 2.5, 5 and 15 c/d as
center frequencies. The predictions for these forms of the
model were similarly poor.

For a third model of spatial frequency interaction in
metacontrast, assume that amount of masking is related to the
degree of similarity between the frequency spectra of target
and mask as was assumed for the second model. However, let
similarity between the frequency spectra of the stimuli be
measured by the ratio of target excitation of a single frequen-
cy channel with limited bandwidth to the mask excitation of that
same channel. It was assumed that channel excitation corre-
sponded to the area beneath the Fourier transform of a stimulus
within particular limits of integration. The modulating fre-
cuencies of the masks, 2.5, 5, 10, and 15 c/d, were chosen as
representative center frequencies for the hypothesized channel.
The frequency spectrum of each stimulus individually was inte-
grated within various limits (see Table 15). The ratios of
these areas, area of target spectrum to area of mask spectrum
within the same set of limits, was then obtained as a measure
of spectra similarity. The set of ratios for one target with
the set of five masks within a particular set of limits was norm-
alized with respect to the largest of the ten ratios for the
two targets.
Two interpretations of the ratios were made. The first interpretation is that amount of masking depends on similarity between the frequency spectra of target and mask such that a ratio of 1.0 of target frequency to mask frequency should yield the most masking. Deviations from 1.0, either smaller or greater than 1.0, were interpreted as a prediction of less masking. To scale the model results on a normalized scale, from 0.0 to 1.0, the reciprocals of ratios greater than one were taken. The results of the model for ratios computed with respect to the narrowest bandwidth shown in Table 15 are depicted in Figure 61. It is clear that none of the sets of ratios approximate the data. The closest match of model to data occurs with the center frequency at 5 c/d for the data of observer 1 for the Gate target (see Figures 54b or 59). However, the model predicts a much greater difference between the effectiveness of the 5 c/d mask and the other masks than occurs in the data. Secondly, the model predicts a corresponding curve for the data for the 5 c/d target which does not fit the data at all.

The second interpretation of the ratios is that the greater the amount of masking, the smaller should be the target to mask frequency ratio. The assumption is that masking occurs to the extent that the mask stimulus has frequency components of greater magnitude about some critical frequency than does the target. To test this hypothesis, the reciprocals of the target to mask frequency ratios were taken and normalized with
Fig. 61. Target/Mask ratios of areas beneath the frequency spectra of the stimuli within a narrow bandwidth (to first zero on either side of the center frequency) about several center frequencies. Center frequencies are 2.5 c/d, \(\infty\); 5 c/d, \(\Delta\); 10 c/d, \(\square\); and 15 c/d, \(\bullet\). respect to the largest of the ten ratios for a particular condition. The ratios for the narrowest bandwidth condition are shown in Figure 62. In all cases, the graph of the predictions of the model are either multi-peaked, or, for the 15 c/d masks, a monotonically increasing curve. The data are not fit well by the models. The results of the model using the wider bandwidth (to the second zero on either side of the center frequency) do not correspond any better to the data. The predictions are quite like those for the model using the narrower bandwidth. Neither are the predictions of the model improved if the frequency spectrum of the stimulus is normalized prior to integration.
Temporal Characteristics of the Data

The ISIs at which the greatest amount of masking occurred for a particular target-mask combination of 1' separation are plotted in Figure 63. The data do not show a clear trend of change in ISI with respect to separation although the data for the two observers for the 5 c/d target are somewhat similar. As discussed in Chapter IV, a lateral inhibition hypothesis would predict that, for a given target, a mask with more luminance at its edge would produce a more rapid change in graded neural potentials resulting in a faster rise time for the inhibitory component. This increase in rise time would predict a shift of the ISI at which the greatest amount of masking occurred to longer ISIs for masks with more edge luminance. The ranking
Fig. 63. ISI in milliseconds at which peak masking occurred for each target-mask combination at a target-mask separation of 1'. For the data of observer 1, o—o, and observer 2, Δ—Δ.

of the five masks in terms of edge luminance is a function of edge width definition as was shown in Figure 55. Consider the ranking of the masks in terms of edge luminance where an edge is defined as the mask luminance within 4' of the edge of the mask. The ranking of the mask stimuli from much edge luminance to little edge luminance is as follows: (1) 2.5 c/d, (2) 5 c/d, (3) 10 c/d, (4.5) Gate and (4.5) 15 c/d mask. For the lateral inhibition hypothesis to be supported, a ranking of the ISI at which peak masking occurred for each target-mask combination from long interval to short interval should be identical to the above ranking. These rankings of the masks for the two targets are shown in Table 17. It is clear than the rankings do not
Table 17

Ranking of masks in terms of ISI for which peak masking was obtained for each target for observer 1, 01, and observer 2, 02, from longest to shortest.

<table>
<thead>
<tr>
<th>Gate Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
</tr>
<tr>
<td>(1) 5 c/d (3.5) Gate (3.5) 2.5 c/d (3.5) 10 c/d (3.5) 15 c/d</td>
</tr>
<tr>
<td>02</td>
</tr>
<tr>
<td>(3) Gate (3) 2.5 c/d (3) 5 c/d (3) 10 c/d (3) 15 c/d</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5 c/d Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
</tr>
<tr>
<td>(1) 15 c/d (3) Gate (3) 2.5 c/d (3) 5 c/d (3) 10 c/d</td>
</tr>
<tr>
<td>02</td>
</tr>
<tr>
<td>(2.5) Gate (2.5) 5 c/d (2.5) 10 c/d (2.5) 15 c/d (5) 2.5 c/d</td>
</tr>
</tbody>
</table>

correspond to the ranking predicted by the lateral inhibition hypothesis. In fact, as occurred with the edge gradient data (see Chapter IV), the temporal trend of the data is almost the reverse of the lateral inhibition prediction. For both observers for the 5 c/d target, the ISI at which the greatest masking occurred for the 2.5 c/d mask is shorter than that for any other mask.

When the data are evaluated from the point of view of differences in target edge luminance for a constant mask, the evidence again does not support a lateral inhibition interpretation. If the datum for a particular observer for the Gate target for each mask in Figure 63 is compared to the correspond-
ing point for that observer for the 5 c/d target in Figure 63, it can be seen that there is no clear trend of changes in ISI with changes in target edge luminance. For the data of both observers, the comparison of the two targets with respect to changes in ISI for each mask is split three to two. A lateral inhibition model would predict that, to obtain maximum masking for a target with greater edge luminance (the 5 c/d target), a shift to shorter ISIs would occur (see Chapter IV). However, if any shift does occur, it is to longer, not shorter, ISIs for the 5 c/d target.

A different test of the lateral inhibition model is that of a temporal shift in the ISI at which the greatest amount of masking occurs as the distance between the target and mask increases. As target-mask separation increases, the model predicts a shift to shorter ISIs (see Chapter IV). Table 18 shows the ISIs at which the greatest amount of masking occurred for each target for the first three target-mask separations. Nearly every temporal shift is to longer ISIs with increasing separation or else ISI is a constant. Again, this shift is in the opposite direction to that predicted by a lateral inhibition model.

The temporal data do not support a lateral inhibition interpretation. Because metacontrast depends on the interaction of the target and mask information (target X mask interaction, \( p < .01 \)), the temporal shifts in the ISI at which greatest masking
occurs are most likely a function of such an interaction. However, the target X mask X ISI interaction was significant for the data of observer 2 \((p < .01)\) but not for the data of observer 1 \((p = .25)\). This discrepancy is difficult to interpret. An hypothesis which is possible to evaluate, however, is that spatial frequency information is encoded temporally. If this assumption were true, then differences in frequency should show up as differences in ISI for peak masking for different masks. For example, if increasing frequency were encoded as decreasing frequency of firing, then the higher frequency masks should show a shift to shorter ISIs. This prediction assumes that a lower frequency of firing will result in a slower inhibitory component. The corresponding high frequency mask would have to be shifted to shorter ISIs for maximum effect. However, the data do not support such an interpretation.

It is interesting that the data for both observers for the 5 c/d target agree in that the 2.5 c/d mask shows the greatest amount of masking at the shortest ISI. In other respects, however, the temporal data for the two observers is difficult to interpret. It is not consistent with a lateral inhibition hypothesis or with a hypothesis based on the amount of mask luminance near the edge of the target. Neither are the temporal data consistent with a simple hypothesis of temporal encoding of frequency. It is possible, though, that if metacontrast is a function of two stages of target-mask interference, such as
Table 13

ISI in milliseconds at which the greatest amount of masking occurred for each target-mask combination for separations of 1', 4', and 12'.

<table>
<thead>
<tr>
<th>Target Separation</th>
<th>Observer 1</th>
<th>Observer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1'</td>
<td>Gate 40</td>
<td>2.5 40</td>
</tr>
<tr>
<td>4'</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>12'</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>5 c/d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1'</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>4'</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>12'</td>
<td>100</td>
<td>60</td>
</tr>
</tbody>
</table>

due to an edge mechanism and a subsequent frequency interaction, the temporal effects of the two mechanisms might be rather complex.
Metacontrast and Contour Information

Metacontrast is a function, in part, of the contour information of the masking stimuli. The amount of masking which is obtained depends on the luminance distribution at the edge of both the target and the mask. The data in the first part of the experiment for the Gate target with the edge gradient stimuli (Sine R, Sine A, Gate and Batman) as masks suggest that the mask feature important to visual masking is the weighted mask luminance at the edge of the target. The data support this suggestion only in part because of the imperfect quantitative fit to the masking data of the predictions based on the weighting function of Growney and Weisstein (1972). On the other hand, the qualitative fit of the model to the data was quite good. This suggests strongly that information such as weighted mask luminance at the edge of the target is of fundamental importance in metacontrast.

The target feature which seems important to the masking effect is not like the mask feature of weighted mask luminance. The effects of the target were not fit well by the predictions of the weighting function which described the effects of the mask in the first part of the study. The masking results for different targets as a function of the Batman mask were fit well, instead, by a model based on the information corresponding
to the convolution of the target stimulus function with the line spread function described by Campbell et. al. (1969) within 4' of visual angle of the edge of the target. This measure is not similar to what might be expected from the operation of an antisymmetric edge mechanism in visual processing. However, it is a measure of the effect of target luminance near the edge of the target.

The edge detector model of Shapley and Tolhurst (1973) is a simple model; yet, it takes into account the target-mask interaction which is suggested by the data of the first part of this study. In terms of metacontrast, the model could work as follows: (1) the target flash optimally excites an antisymmetric edge detector, whose center coincides with the neural projection of the target edge. The positive side of the detector overlaps the neural projection corresponding to the area immediately inside the target edge. The negative side of the detector is lateral to the target edge projection. (2) The mask flash excites the negative side of the edge detector. (3) The output of the edge detector, which is the sum of the excitation of the target and the inhibition contributed by the mask, corresponds to the apparent brightness of the target (Shapley & Tolhurst, 1973). Although several characteristics of the data support this edge detector hypothesis, the model does not satisfy completely the requirements for a model of metacontrast. First, the sensitivity profile of the mechanism
described by Shapley and Tolhurst was antisymmetric about the edge; the positive weights on the target side of the edge were approximately equal in magnitude to the negative weights on the mask side of the edge. However, the contour information of the target in metacontrast differs from the contour information of the mask, as shown in the first part of this study (see Chapter IV). The target and mask contour information in metacontrast are not antisymmetric in character. In fact, this observation, as discussed earlier in this paper, is consistent with the information processing hypothesis of metacontrast, that the neural code corresponding to the mask at one stage of processing interferes with the neural code corresponding to the target at a more advanced stage of processing. This view is supported by the nonzero ISI at which peak masking occurs. On the other hand, it is difficult to understand why the temporal neural characteristics of the positive side of the edge detector should be so much slower in developing than those of the negative side of the edge detector; this would be a necessary condition if the edge detector model is to predict the temporal characteristics of metacontrast. These two discrepancies with the edge detector model, the lack of antisymmetry in the contour information of target and mask and the nonzero ISI at which peak masking occurs, suggest that a single cell interpretation of the edge detector (e.g., Shapley & Tolhurst, 1973) is inappropriate for metacontrast. A more
general interpretation of the edge detector hypothesis for metacontrast is in terms of an edge detector system, some of whose components have characteristics similar to the sensitivity profile described by Shapley and Tolhurst.

Different processing stages of this edge detector system may be tapped in metacontrast experiments, depending on the spatial separation of the target and mask. The antisymmetric edge mechanism described by Shapley and Tolhurst may characterize one such processing stage. This stage corresponds to a stimulus arrangement in metacontrast where the mask is spatially adjacent to the target. The negative weights lateral to the edge of the target in a metacontrast experiment (Growney & Weisstein, 1972) are remarkably similar to the sensitivity profile of the negative side of the edge detector mechanism (Shapley & Tolhurst, 1973). The data of this experiment are also consistent with this interpretation. For the conditions in which the target and mask were adjacent (target-mask separation of 1'), the general characteristics of the data were fit, albeit roughly, by a model based on the weighting function of Growney and Weisstein (1972). This was true for the stimuli which differed primarily in edge gradient (see Chapter IV) but not for the frequency stimuli (see Chapter V and the discussion later in this chapter).

The spatial extent of the negative side of the edge detector mechanism described above is probably smaller than 10'.
of visual angle (Growney & Weisstein, 1972; Shapley & Tolhurst, 1973). However, targets and masks, which are not immediately adjacent but are at varying spatial separations, show decrements in the apparent brightness of the target for target-edge to mask-edge separations of one to three degrees (Alpern, 1953; Weisstein & Growney, 1969; Cox, Growney & Weisstein, in preparation). This large spatial extent of negative weights was replicated in this study; for most target-mask combinations, some masking was obtained at a target-mask separation of $84'$. This spatial range of masking would certainly not be predicted by the edge detector mechanism described earlier. This observation implies that an additional spatial mechanism is involved in metacontrast. The data do not support the hypothesis, however, that this spatial mechanism is form-specific (see, for example, Growney & Weisstein, 1972 and the discussion later in this chapter).

On the other hand, it is possible that this large spatial mechanism (meaning large in spatial extent) is another edge detector. This edge detector may have properties similar to those of the cortical cells described by Bishop, Henry and Smith (1971) which had a lateral inhibitory surround of $2^\circ$ radius. The output of such a detector might also contribute to the apparent brightness of the target. The near edge of the mask might serve as inhibitory input to this edge mechanism (Weisstein, 1972). Shapley and Tolhurst (1973) suggested that a population of edge detectors might be operative in visual
processing and function as independent channels in a linear manner. Bekesy (1968) has hypothesized the existence of two neural units in suprathreshold visual processing which are similar in spatial extent to the two spatial mechanisms implicated by metacontrast data. Although the two units suggested by Bekesy were symmetric units, it is certainly possible that a suitable model of metacontrast could consist of two kinds of edge detector units, one small (10') and one large (20') in inhibitory radius, with one or both of the units described by antisymmetric spatial characteristics.

If one were to assume a two-component, edge detector system, there would be an additional reason, other than individual weighting function differences, why the frequency stimuli were not quantitatively fit by the predictions of a weighting function model of metacontrast. The luminance of the internal contours of the frequency stimuli, which is similar to out of focus alternating white and black bars, may not yield a weighted sum in the same manner as a Gate of uniform luminance. Nonlinearities, similar to those reported by Thomas (1968), may be introduced by the alternating white and black segments. The black segments, for example, may not function simply as zero luminance but may increase the contrast of the other stripes; in effect, the weights may change as a function of mask edge gradient. On the other hand, the contribution of the second edge detector
component, which is large in spatial extent, is unknown for a masking stimulus with multiple edges, internal contours. This contribution may or may not be linear with respect to space. Further, it is not clear how the two edge detector components interact, if at all, or how the output of the two components is summed.

Another interpretation of the target-mask interaction, different from the above discussion, is that metacontrast could also be a result of the inhibitory effects of the target acting upon itself under certain conditions. This kind of activity would be an example of spatial self-inhibition. There is, at least, some previous evidence of temporal self-inhibition in psychophysical phenomena, the classical example of which is the Broca-Sulzer effect (e.g., Graham, 1965). In the Broca-Sulzer effect, the apparent brightness of a briefly flashed stimulus increases as duration increases to a critical value; for durations longer than the critical value, the apparent brightness of the stimulus decreases to a steady-state value. The suggestion that spatial self-inhibition describes the activity of the target in metacontrast is based primarily on the data which were obtained with the Batman mask. The model which was tested predicted that the decrease in target brightness should be proportional to the convolution between the luminance distribution of the stimulus and a symmetrical weighting function which is a composite description of visual system spatial
characteristics; the integral was taken over 4' of visual angle near the inside of the edge of the stimulus. The predictions of this model match the data of both observers quite well with the Batman mask; the amount of masking which was obtained with each target is in proportion to the convolution described above. This correspondence means that the decrement in apparent brightness of the target is in proportion to one measure of target luminance near the edge of the target. This could be an example of spatial self-inhibition which occurs, at least, with mask-stimuli with sharply defined contours. In some respects the data for the Gate mask are also similar to the data for the Batman mask, slightly reduced in amplitude. This is true for the data of observer 2; it is only partially true for the data of observer 1, which resemble more the convolution within 2', instead of 4', inside of the edge of the target. Although the target data for the other masks do not follow the qualitative predictions of the above description, the data might be consistent with the assumption that the effectiveness of target self-inhibition is dependent upon some measure of mask edge luminance.

This second interpretation is certainly a tenuous description of what might happen in neural processing to yield the masking effect. Its major virtue may only be to emphasize that metacontrast is, in part, an interaction of neural signals corresponding to the contour information of the masking stimuli.
At the very least, the data are consistent with the hypothesis that the neural code corresponding to the mask at one level of visual processing interferes with the neural code corresponding to the target at a different level of visual processing. The mask does not have to undergo the same kind of information processing as does the target in order to interfere with the target. The levels of processing may or may not correspond to weighted luminance of the mask and self-inhibition in proportion to target edge luminance.

**Metacontrast and Frequency Coding**

None of the models of spatial frequency interaction which were tested yielded predictions which corresponded to the general characteristics of the data. Certainly, these models are not exhaustive of the possible models which might be tested. For the models which were tested, however, no support was obtained for the hypothesis that metacontrast depends on the similarity of frequency components between the target and mask, either over the entire range of frequencies or over the particular channels or combination of channels which were considered. In particular, a model based on similarity of spatial frequency components would predict very little change in amount of masking with increasing spatial separation between the target and mask for the stimuli of this experiment. However, as in other metacontrast experiments (e.g., Weisstein & Growney, 1969), the amount of masking decreases sharply with increasing target-
mask separation. This decrease is inconsistent with the invariance with respect to location of the Fourier components of spatially translated stimuli. The cosine modulation of the frequency transform resulting from the lateral shifts in location does not change the general characteristics of the transform to a marked extent. The amount of masking should not change to the extent shown in the data on the assumption that a frequency coding underlies metacontrast. Marked decreases in amount of masking would be expected, on the other hand, if an edge detector system mediated metacontrast. The weights which described the relative contribution at each spatial point of a component of the edge detector system would probably decrease in magnitude with increasing distance from the edge of the target (e.g., see Growney & Weisstein, 1972).

The development of the frequency models may not have been entirely without application, however. It is interesting to consider the threshold changes for sine wave gratings as a result of adapting to sinusoidal gratings of 5.5 c/d and 16 c/d in the data of Sullivan, Georgeson and Oatley (1972; these results are depicted in their Figures 6 and 7, respectively). Because the threshold changes are confined to a narrow range of frequencies centered about the frequency of the adapting grating, such adaptation results are thought to be due to single channel mechanisms (e.g., Blakemore & Campbell, 1969). The adapting grating lowers the sensitivity of a particular
frequency-selective mechanism; subsequent gratings will not be detected as well, depending on their similarity to the frequency of the adapting grating. One measure of similarity is the cross-correlation of the frequency spectra of the two stimuli about a center frequency corresponding to the frequency of the adapting channel, within limits defining the bandwidth of the channel. In this respect, it may be noteworthy that the threshold changes due to an adapting grating of 5.5 c/d are similar in their general characteristics to the cross-correlation of the frequency spectra of the 5 c/d target with the different frequency-modulated masks, about a center frequency of 5 c/d with wide bandwidth, 2.5 c/d to 7.5 c/d (see Figure 60b in Chapter V). The fit is very good for the data of observer TF; it is not as good for the data of the other observers in the 15 c/d range of frequency. The two situations are not comparable, however, unless it can be assumed that the neural signals corresponding to amplitudes of the frequency spectra for the different, aperiodic, frequency-modulated stimuli are in some way proportional to the neural signals corresponding to the amplitudes of the frequency spectra of the periodic, adapting gratings within the limits defined by the channel bandwidth. Under the same assumption, the data for the 16 c/d adapting grating in the study of Sullivan et. al. are similar to the cross-correlation as described above evaluated about a center frequency of 15 c/d within the limits, 12.5 c/d to 17.5 c/d
(see Figure 60b in Chapter V). This second comparison of the cross-correlation results to the data of Sullivan et. al. is not really comparable because the cross-correlation was evaluated with the 5 c/d target. However, the comparison is illustrative in suggesting that an evaluation of the similarity of two stimuli about a centering frequency of 15 c/d within some bandwidth might manifest the general data characteristics obtained by Sullivan et. al.

Another characteristic of the data is not consonant with the predictions of models of spatial frequency. The Sine A stimulus was clearly much less effective than all other masks, except for Sine R. Yet, the Sine A stimulus was a frequency-modulated Gate window of 1.25 c/d. If the center of the target can be considered to be the center of the two-dimensional spatial coordinate system describing position in the visual field, then the Sine A stimulus did not differ significantly in phase from the other frequency-modulated Gate stimuli at a target-mask separation of 1'. The masking of the Gate target by the 1.25 c/d stimulus, then, should have been much more effective, equal in amount to some value of masking between the results for the Gate mask and the 2.5 c/d mask. Observation of the stimulus display, however, gave the subjective impression that the Sine A stimulus could not be as effective as the other stimuli; it was simply not well-defined as an object in the visual field. The other frequency-modulated masks were edged
with 1/4 cycles of peak luminance. The processing which occurred for the neural information corresponding to the frequency-modulated masks seems to have been contingent on the edge definition, contour information, of the stimuli. Whether or not this contour information is identical to high frequency information will be discussed shortly. However, the importance of contour information for the frequency stimuli is clearly indicated.

The target and mask in a metacontrast experiment do not seem to be evaluated in terms of the similarity of their frequency spectra. It is possible that the truncation of the sinusoidal gratings by the Gate window at the peak of a cycle, which created edges, biased the visual processing mechanisms so that they did not process the stimuli in terms of their frequencies. The presence of contour information could serve, for example, to switch the visual processing mechanisms to a particular model of rapid processing in terms of contour information.

Another possibility, which could be congruent with the above observation, is that metacontrast is not a function of frequency-coding because visual processing generally does not function in terms of the spatial Fourier components which correspond to visual stimuli. There are, at least, two interpretations of the function of a frequency coding in visual processing which are consistent with this suggestion. These
two interpretations are not necessarily mutually exclusive. Evidence suggesting that the visual system actually performs a Fourier analysis upon the neural code corresponding to stimuli and uses information proportional to the Fourier components has been obtained under forward-masking (adaptation) conditions. One interpretation of such data is that a Fourier-like process occurs in parallel with other information processes, such as an edge processing system. The function of the Fourier process might be to determine the similarity of temporally contiguous stimuli in order to bias or prepare the system for subsequent processing. A Fourier process might function to desensitize the system to redundant stimulation on the basis of higher-order properties of the stimuli, such as form. Although important to the understanding of some visual system processes, such a system might not be a general preprocessor of all visual stimuli. It would be of limited applicability in understanding visual processing generally, and backward masking in particular. Metacontrast would be a function of other mechanisms.

There is a second interpretation of the function of a frequency coding which is consistent with the hypothesis that a Fourier process in vision is a special, not a general, process which has limited applicability. A frequency-coding could be a peripheral process which occurs early in the visual pathway, at least prior to the stage where the input from the two eyes
converges. The function of such a recoding could be to pre-process the neural code corresponding to a visual stimulus, for example, to minimize the effects of some types of visual noise by means of low frequency filtering. There is some evidence which suggests that the data of forward masking experiments are influenced principally, by processing mechanisms early in the visual pathway (Turvey, 1973). Forward masking effects are usually very pronounced under monoptic conditions of patterned stimulus presentation but are seldom found under dichoptic conditions (Kahneman, 1968; Turvey, 1973). These results suggest that forward masking effects are primarily determined by a processing which occurs prior to the combination of information from the two eyes. The effects of a Fourier-like process could occur, and be limited to, such a peripheral level of processing. Independent evidence in support of this hypothesis has been contributed by Julesz (1971). The dichoptic presentation of coherent visual scenes can usually be achieved even though the individual left-eye and right-eye stimuli appear, monocularly, like random dots. However, if the left eye receives only the low frequencies corresponding to a square-wave grating, and the right eye receives only the corresponding high frequencies, the observer is unable to fuse the dichoptically-presented stimulus to achieve stereopsis (Julesz, 1971). This result suggests that a frequency processing, if it occurs, takes place prior to the visual processing level where the individual ocular inputs are combined.
A Fourier-like process might be tapped, therefore, by the particular stimulus conditions of a forward masking experiment. The neural code corresponding to the luminance distribution of the stimuli may be recoded early in visual processing in terms of some measure corresponding to the spatial Fourier components of the stimuli. Because metacontrast does not seem to be a function of the amplitudes of these Fourier components or their interaction (to the extent tested), stimulus conditions other than those of a forward masking experiment may tap other mechanisms which are parallel to and independent of the frequency-coding channels. As an alternate possibility, if all visual stimuli undergo a Fourier transformation, processing subsequent to such a transformation, as metacontrast, may not be in proportion to the Fourier components; this suggests that a recoding takes place subsequent to the Fourier-like process. The failure to find the effects of a frequency coding in metacontrast is consistent with these suggestions. Metacontrast can be obtained monoptically or dichoptically and, most probably, taps central processing components (Weisstein, 1972).

Contour Information as High Spatial Frequency Information

Although there are frequency-specific effects in psychophysical experiments (e.g., Blakemore and Campbell, 1969), the contour information corresponding to the stimuli in a metacontrast experiment does not function specifically as high spatial frequency information. It would have been possible to show a
distinction between the function of high spatial frequency information and contour information if, in fact, one of the models of spatial frequency interaction with a high center frequency had fit the characteristics of the data. However, none of these models fit the data. As discussed above, there are several arguments suggesting that frequency information is used only in a limited number of visual processing channels or that the effect of such frequency information is limited to early processing stages. Metacontrast seems to be a function of an edge detector system which is independent of the visual channels which are selectively sensitive to certain spatial frequencies and seems to occur at a relatively high central stage of visual processing.

Metacontrast and the Contrast of Masking Stimuli

The masking of the 5 c/d target corresponded in several important ways to the contrast of the masking stimuli. The masking data for each observer matched the contrast results for three of the five masks. More importantly, the contrast results matched the individual data characteristics of each of the observers.

The general correspondence of the contrast of the masking stimuli to the masking of the 5 c/d target which was obtained by using these masking stimuli could have occurred on the assumption that a single channel mechanism evaluated the contrast of the masking stimuli and attenuated the neural signal correspond-
ing to the target in proportion to the contrast measure. It is quite possible, though, that the important property of the masking stimulus was not the contrast of the stimuli but some other quantity in proportion to the contrast of the masking stimuli. One such measure could be the peak-to-trough difference in the output of a mechanism, the characteristics of which would correspond to the visual transfer function. Such a measure would show attenuation with masking stimuli at both high and low modulating frequencies; at a modulating frequency of zero, a peak-to-trough difference might be evaluated at the edge of the mask. This model would have predicted measurable masking instead of zero masking by the Gate mask. A different version of this model would involve a comparison of the peak-to-trough difference of the mask to the peak-to-trough difference of the target. Because the target peak-to-trough difference is a constant across masks, any ratios, for example, of mask peak-to-trough difference to target peak-to-trough would be in proportion to the mask peak-to-trough difference. This version of the model has the advantage of suggesting a reason for the difference between targets, although it is not clear how the peak-to-trough difference of the Gate target was evaluated in neural processing. One possibility is that this difference is measured at the edge of stimuli without internal contours; however, this possibility was tested with respect to the application of Land and McCann's model to metacontrast without success.
It is possible that the differences between the data of the two observers for the frequency stimuli may be due to two factors: (1) the combined effects of individual weighting function differences and (2) the dependence of the spatial distribution of the negative weights upon the target contour information. This second possibility is suggested by the dependence of mask effectiveness on the target luminance at the edge of the target. This two-factor hypothesis would imply that the contrast data may be the output of the same edge detector system which contributes to the phenomenon of metacontrast or are, at least, influenced strongly by the output of the edge detector system. This view has the merit of attributing the similarity between the contrast and metacontrast data to the influence of one system, an edge detector system. Of course, it is conceivable that the similar contrast and metacontrast data are the output of two different mechanisms. However, because of the general importance of contour information to the experience of apparent brightness, it seems quite likely that the similar results could be the effect of the same edge detector system.

Other Hypotheses of the Function of Edge Information in Metacontrast

The data of this experiment support Werner's (1935) hypothesis that the metacontrast involves the interaction of the neural code corresponding to the mask with the neural code
corresponding to the target. Target information, however, seems to play a greater role than that suggested by Werner. The metacontrast data are not consistent with the hypothesis that the neural code for the edges of the target is assimilated by the neural code for the edges of the mask. As discussed in Chapter I, this hypothesis may imply that the extent to which the edges of the target are assimilated is a function of the intensity (luminance) at the edges of the target. A target with poorly defined edges, such as Sine A, should be masked quite effectively, on the assumption that the neural signal corresponding to the edges of the target is easily assimilated. The data show, however, that exactly the reverse occurs. Targets with poorly defined edges are fairly resistant to masking. Targets with sharply defined edges, Gate and Batman, were masked to a much greater extent than were Sine A and Sine R. In fact, the Batman target is masked to a greater extent than the Gate target for three of the four possible target-mask combinations in the data of each observer. Amount of masking, therefore, seems to be directly related to the luminance at the edge of the target.

An edge detector hypothesis which explains masking solely in terms of the mask exciting the inhibitory flanks of an edge detector (see Chapter I) is not supported by these data. That presentation, like Werner's, did not allow for the importance of the contour information of the target. To say, simply, that
the neural code for the edges of the target is nulled by the neural code for the edges of the mask omits any account of the manner in which the target edge neural code changes the effectiveness of the mask edge neural code. This reciprocal relationship between the neural signals corresponding to the edges of the masking stimuli as discussed above seems fundamental to the metacontrast effect.

The incompletely-processed-mask hypothesis (Weisstein, 1972) received some support from the data although not as hypothesized. This hypothesis accounts for the fast rise time of the visual system response to the mask by assuming that the mask undergoes only incomplete processing before it is able to interfere with the processing of the target. The data support this hypothesis to the extent that the neural information utilized in visual processing for the masking effect differs for the target and mask (as discussed earlier in this chapter). This difference suggests that the interaction between the neural signals corresponding to the edges of the two stimuli occurs when the stimuli are at two different stages of processing. If weighted mask luminance is important to the processing of the mask, then the neural signal corresponding to the edges of the mask may be at a comparatively early stage in visual processing where the neural code for the edges of the mask have been weighted and summarized in a manner that is still closely related to the luminance of the actual stimulus. On the other
hand, suppose that the neural edge information of the target which is important to the masking effect is related to the convolution of the target luminance distribution and some line spread function (such as that described by Campbell et al., 1969) as measured within 4' of the target edge. The neural signal corresponding to the edges of the target, then, may be at a later stage in visual processing, nearly ready for output from the mechanism whose characteristics are defined by the line spread function. In fact, a more adequate spatial model of metacontrast might compare amount of masking to some measure relating the neural edge information of the target and mask under these assumptions.

However, the incompletely-processed-mask hypothesis was not supported by the temporal characteristics of the data, under the assumption that differences in processing time for different edge gradients are manifested in shifts in the ISI for which the greatest amount of masking occurs. Assuming that the neural signal which summarizes the luminance at the edge of the masking stimulus operates in a manner analogous, at least, to lateral inhibition, the incompletely-processed-mask hypothesis predicted that (1) a mask with more luminance at its edge would produce a more rapid change in graded neural potentials resulting in a shift of the ISI at which the greatest amount of masking occurs to longer ISIs, and (2) a target with more luminance at its edge would produce a more rapid change in
graded neural potentials resulting in a shift of the ISI at which the greatest amount of masking occurs to shorter ISIs. Clear support was not obtained for either of these predictions. Neither do the data support predictions based on a lateral inhibition hypothesis of shifts in the ISI at which the greatest amount of masking occurs to shorter ISIs for masks at increasing spatial separations from the target. To the extent that such shifts occur for the first three target-mask separations of 1', 4' and 12', the shifts are to longer ISIs with increasing separation. The characteristics of the temporal data are not consistent with an interpretation in terms of lateral inhibition of the two-factor theory of metacontrast (Weisstein, 1968; 1972). This discrepancy is not surprising if it can be assumed that the temporal characteristics of the data are a function chiefly of the differences in processing stages for the target and mask neural signals.

The hypothesis that metacontrast is a function of a size detector whose excitatory center is equal in width (visual angle) to the width of the target or mask stimulus is not supported by these data (see Thomas, 1970, for a discussion of this hypothesis with respect to the detectibility of a stimulus). If this had been the case, the Sine A stimulus should have been as effective or even more effective as a masking stimulus than the Gate target, depending on the sensitivity of the excitatory center of the hypothesized size detector with respect to
space. Neither does metacontrast seem to be a function of a sum of the activity of a size detector for the center of the stimulus combined with the activity of a pair of edge detectors (see Thomas & Kerr, 1971, for a discussion of the function of such a sum of activity with respect to the detectibility of a stimulus). If this had been the case, the 2.5 c/d mask should have always been more effective than the 5 c/d or 10 c/d masks. Further, the Batman mask should not have been more effective than the 2.5 c/d mask unless added assumptions can be made about the relative sensitivity of the edge detectors with respect to the center detector.

**Metacontrast and Form Similarity**

Little evidence was obtained which supported the hypothesis that amount of masking varies as a function of the similarity in form of the masking stimuli (Uttal, 1970). For the data of observer 2, the Gate target was masked best by the Gate mask, and to only a slightly lesser extent by the 15 c/d mask, which approaches the Gate mask in uniformity of distributed luminance; the 5 c/d target was masked best by the 5 c/d mask. This correspondence was not observed in the data of observer 1. Neither was it found in the data of either observer for the stimuli which differed primarily in edge gradient. These data are in agreement with those of Cox (1972), where a rectangular target was combined with rectangular and trapezoidal masks in a metacontrast design. Masking did not decrease in
amount as the mask changed in shape from rectangular to trapezoidal. Cox (1972) found no evidence in support of a form specificity hypothesis. It is probably significant that the stimuli used by Cox in her study and the stimuli used in this study differ from the stimuli used by Uttal (1970) in two important respects: (1) Uttal's stimuli were outline figures, not solid figures as the stimuli in Cox's study and the Gate figures in this study, and (2) the edges of Uttal's masking stimuli were not at a constant spatial separation from the target at all points; the spatial separation between the rectangular target and the triangular mask, for example, varied from a minimum at the base of the triangle to a maximum at the peak of the triangle. The masking effect which Uttal has described must be a function of higher-order factors in which the form of the masking stimulus is represented. The outline figures used by Uttal, such as the triangle masks, minimized energy differences among stimuli which may have facilitated the appearance in the data of higher-order processing effects (see, for example, Turvey, 1973). Because Uttal's stimuli were not all rectangular, the target and mask might not have stimulated similar or spatially adjacent orientation-specific detectors. The spatially contiguous edges of the targets and masks in this study and the study of Cox (1972) could optimally stimulate such orientation-specific detectors. This observation is important to the extent that the edge detector system is related
to orientation-specific detectors (Gilinsky, 1968) or to the inhibitory effects of such detectors (Blakemore, Carpenter & Georgeson, 1970). The large spatial extent of metacontrast for stimulus conditions in which the separation between the target and mask is varied is most likely the function of a second edge detector system. The effects of form similarity between the target and mask were not observed in the data of this study even at a separation of 12'; at this distance, the effects of the edge detector system, described by Crowney and Weisstein (1972) and Shapley and Tolhurst (1973), should have been minimal. However, the characteristics of the masking effects did not change substantially; they certainly did not change in the direction of predictions based on the form similarity hypothesis.
CHAPTER VII

CONCLUSION

This study was an extensive parametric investigation of the phenomenon of metacontrast. Metacontrast was studied as a function of luminance gradients at the edge of the masking stimuli, Fourier components of the masking stimuli, and the temporal and spatial separation between the masking stimuli. The data strongly suggest that metacontrast is a function of an edge detection system in human vision. Although the importance of contour information has long been hypothesized as basic to metacontrast (e.g., Werner, 1935; Battersby & Wagman, 1962; Weisstein, 1972), the data of this study are the most direct evidence to date which support the hypothesis that an edge system underlies metacontrast.

This suggestion (Weisstein, 1969; 1972) that metacontrast is an especially useful tool with which to investigate some characteristics of higher-order visual processing has been supported by these data. By varying the luminance gradients at the edge of the target and mask, it has been possible to assess the relative contribution of the contour information of the target and mask to the masking effect. Masking varies as a function of the luminance gradient at the edge of the masking stimulus. However, the effects of the target and mask are not reciprocal. The contour information of the mask which is important in the metacontrast effect is weighted mask luminance
near the edge of the target. A previous description of the magnitude and spatial extent of these weights (Growney & Weisstein, 1972; see also Shapley & Tolhurst, 1973) was partially replicated under the different stimulus conditions of this study. However, the contour information of the target cannot be described in terms of the weighting function which described the effects of the mask. Although the effectiveness of the mask near the target is consistent with the description of the negative side of the antisymmetric edge detector (Shapley & Tolhurst, 1973), the effectiveness of the target contour information is not consistent with the description of the positive side of the edge detector. This nonreciprocity is consistent with an information processing model of metacontrast consisting of interacting sequential stages at each of which different kinds of processing occur (Weisstein, 1972): the neural code corresponding to the mask at one stage of processing interferes with the processing of the neural code corresponding to the target at a different stage of processing. The nonzero temporal, interstimulus interval between the presentation of target and mask at which peak masking occurs suggests that the neural representation of the target is at a more advanced stage of processing than the neural representation of the mask when the interference occurs.

The data from previous metacontrast studies (e.g., Alpern, 1953; Growney & Weisstein, 1972) have suggested the existence
of more than one underlying, spatial system. By varying the spatial separation between the target and mask in this meta-contrast study, it has been possible to determine that the spatial mechanism with a larger spatial extent is not identical to the mechanism described by Uttal (1970) which yielded form-specific masking. Masking was not a function of the similarity in form between the target and mask, either at a separation of 1' where the effects of the hypothesized smaller edge mechanism (smaller in spatial extent) should have predominated or at a separation of 12' where the effects of the hypothesized larger spatial mechanism should have appeared. The larger spatial mechanism seems better described as another edge mechanism, which, together with the smaller edge mechanism, contributes to the apparent brightness decrement of the target. Those two components may comprise an edge detection system in human vision. It is not clear, however, whether or not these two components function in an independent and linear manner and whether or not they are both antisymmetric in spatial effect. Neither is it known to what extent such a system would contribute to apparent brightness effects, generally, in visual experience.

The spatial and temporal characteristics of this hypothesized edge system have not been precisely specified. However, general qualitative characteristics of part of this system as well as certain quantitative particulars of the system have been successfully predicted. There is an encouraging inter-
study consistency in describing one of the components of this edge system, the smaller edge mechanism (Growney & Weisstein, 1972; Shapley & Tolhurst, 1973). The data of this study are in agreement with characteristics of this edge component and also with the spatial extent of the larger edge mechanism. Some differences in quantitative predictions which were made with respect to the data of this study may well have been a function of individual differences in the parameters of the weighting functions describing these two mechanisms. In order to isolate the contribution of the different spatial mechanisms, it will be desirable in future research to measure the individual weighting function of each observer.

This study failed to find any evidence that the Fourier components of the target and mask are utilized to yield the masking effect. This is an important result because it suggests that a frequency analysis may be of limited applicability to understanding general psychophysical phenomena. The implications of the findings of this study are limited in that only several of the possible models of the use of Fourier components in metaccontrast were tested. However, the characteristics of several of the most reasonable models were studied with negative results. Evidence is accumulating which suggests that such negative results should not be unexpected. As discussed in Chapter VI, the evidence in support of the operation of a Fourier-like process in vision comes primarily from forward-masking studies. The stimulus conditions of these
studies may well tap stages of visual information processing which are peripheral to the processing of the phenomenon of metacontrast.

The results of this study are consistent with a developing model of visual information processing. As first proposed by Campbell & Robson (1968), the visual system does not behave as a single filter which can be characterized by a spatial modulation transfer function (e.g., Cornsweet, 1970). Rather, visual processing seems to consist of a system of parallel, independent channels, all of which may be operative in suprathreshold vision. Previous results, derived from adaptation studies, have suggested that these channels functioned primarily as part of a Fourier-like transformation. The data of this study suggest that, to the extent such a process exists in vision, it need not constitute a transformation which underlies all visual phenomena. As Shapley and Tolhurst (1973) argue, an edge detection system exists in vision and functions in a manner that is independent of the channels which are selectively sensitive to narrow bands of spatial frequencies. The data of this study suggest that the stimulus conditions of metacontrast selectively tap this edge detection system.
REFERENCES


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The dissertation is therefore accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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