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ScienceDirect
Vision Research 47 (2007) 85–107
Vision Research
www.elsevier.com/locate/visres

Detection of Gabor patterns of different sizes, shapes, phases and eccentricities

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Received 31 March 2006; received in revised form 30 August 2006

Abstract

Contrast thresholds of vertical Gabor patterns were measured as a function of their eccentricity, size, shape, and phase using a 2AFC method. The patterns were 4 c/deg and they were presented for 90 or 240 ms. Log thresholds increase linearly with eccentricity at a mean rate of 0.47 dB/wavelength. For patterns centered on the fovea, thresholds decrease as the area of the pattern increases over the entire standard deviation range of 12 wavelengths. The TvA functions are concave up on log–log coordinates. For small patterns there is an interaction between shape and size that depends on phase. Threshold contrast energy is a U-shaped function of area with a minimum in the vicinity of 0.4 wavelength indicating detection by small receptive fields. Observers can discriminate among patterns of different sizes when the patterns are at threshold indicating that more than one mechanism is involved. The results are accounted for by a model in which patterns excite an array of slightly elongated receptive fields that are identical except that their sensitivity decreases exponentially with eccentricity. Excitation is raised to a power and then summed linearly across receptive fields to determine the threshold. The results are equally well described by an internal-noise-limited model. The TvA functions are insufficient to separately estimate the noise and the exponent of the power function. However, an experiment that shows that mixing sizes within the trial sequence has no effect on thresholds, suggests that the limiting noise does not increase with the number of mechanisms monitored.

Keywords: Contrast; Threshold; Receptive field; Size; Models

1. Introduction

Gabor patterns have become widely used in vision research. Consequently, it is desirable to have accurate measurements of sensitivity to Gabor patterns of different sizes, shapes and phases. Such measurements may also contribute to estimating the properties of the receptive fields of human pattern vision mechanisms and the way in which mechanism signals combine to determine thresholds.

There have been many attempts to use psychophysics to determine the receptive fields of the detecting mechanisms. These go back to early measurements of spatial summation. Graham, Brown, and Mote (1939) proposed an explicit model of spatial summation for uniform patches of light, which was in essence a model of the receptive field of the detecting unit. After it became known that receptive fields contain both excitatory and inhibitory regions, a paradigm introduced by Westheimer (1967) came into use. In the Westheimer paradigm a small spot was flashed in the center of a steady disk. As the diameter of the disk increased, the threshold for the flash increased and then decreased. The size at which the threshold reached maximum was taken to be the size of the excitatory region of the detecting field and the size at which the threshold ceased to decrease was taken to be the size of the inhibitory region. Later studies made the context pattern subthreshold and flashed it with the target to minimize adaptation. This came to be called the method of subthreshold

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0042-6989/$ - see front matter
doi:10.1016/j.visres.2006.09.005

summation. Some studies used a line as a target with context lines on either side (Hines, 1976). Many studies were done involving subthreshold summation of gratings. A common paradigm was to reduce the separation between two grating frequencies until linear summation of their effects was obtained. This was shown to be a poor method for estimating the bandwidth of the underlying fields due to complications produced by probability summation (Graham & Robson, 1987). On the assumption that pattern adaptation reduces the sensitivity of receptive fields that respond to the pattern, bandwidths were estimated from adaptation effects by Blakemore and Campbell (1969) and Georgeson and Harris (1984) to be about 1.4 octaves. However, the desensitization model that they used is not a completely adequate account of adaptation (Foley & Chen, 1997). Legge and Foley (1980) and Wilson et al. (1983) used pattern masking to estimate bandwidth. Both studies used a model of masking that assumed that masking depends on the excitation of the detecting field by the mask. It is now clear that masking depends on inhibition produced by the mask and this inhibition is more broadly tuned than is the excitation of the detecting mechanism (Foley, 1994). Further, it is now known that the extent of the mask beyond the target can have a large effect on the magnitude of masking (Yu & Levi, 1997, 1998). Although there are now models that incorporate lateral context effects (Chen & Tyler, 2001; Varadharajan & Foley, 2003; Yu, Klein, & Levi, 2003), none of these newer models is completely satisfactory and none has been used to estimate receptive fields.

Absolute threshold experiments offer another way to find out about pattern mechanisms. There have been numerous studies of absolute contrast thresholds for patterns, some of which have sought to determine the nature of the detecting mechanisms. There is some evidence for receptive fields matched to the stimulus pattern (Hauske, Wolf, & Lupp, 1976; Rovamo, Luntinen, & Nasanen, 1993), even when the pattern is a sharply truncated Gabor pattern (Syvajarvi, Nasanen, & Rovamo, 1999), but other results are inconsistent with these. The evidence generally points to Gabor-like receptive fields, but estimates of their size or shape differ greatly. Most models have used circular Gabor receptive fields that are relatively small, and there is evidence that such fields mediate detection (Watson, Barlow, & Robson, 1983). However, Polat and Tyler (1999) have presented evidence of detection by receptive fields that are greatly elongated in the direction parallel to the stripes. In addition to the shape issue, there is also a lack of agreement about the size of these fields and whether there is more than one size tuned to the same spatial frequency. In practice, our ability to use detection experiments to determine receptive fields depends on the level of accuracy and precision in threshold measurement that can be attained.

The extraction of receptive field estimates from such measurements is fraught with difficulties. The principal difficulty is that for most patterns many different receptive fields are likely to contribute to detection and these fields may vary with the size of the pattern. For example, narrow patterns contain a wide range of spatial frequencies and may stimulate receptive fields tuned to very different spatial frequencies. Large patterns undoubtedly stimulate many receptive fields in different retinal locations, and these may differ in spatial sensitivity.

Our approach is as follows. Our stimuli are Gabor patterns. They have the same form as the two-dimensional Gabor functions that have been shown to describe the spatial sensitivity functions of V1 neurons in monkeys (Ringach, 2002). Their center spatial frequency (4 c/deg) is close to the frequency to which the system is most sensitive at the luminance that we used. This increases the likelihood that receptive fields tuned near to this frequency will detect the patterns. We test this hypothesis by fitting a model based on Gabor receptive fields to our data. We find that a model containing a spatial array of Gabor receptive fields tuned to our pattern frequency, whose responses are power functions of their excitation and are summed linearly, gives a good account of our results.

In addition to varying the size and shape of the patterns, we have varied spatial phase relative to the center of the pattern. We find that for small patterns phase interacts with size and this interaction depends on phase. The model accounts for this effect as well. We also performed related experiments on the effect of eccentricity on thresholds, size discrimination at threshold, and the effect of mixing different sizes of patterns within a block of trials.

2. Background

2.1. Effect of size

There have been many studies of contrast thresholds for sinewave gratings as a function of size. In a 1996 review Garcia-Perez and Sierra-Vazquez (1996) counted 36 such experiments and there have been more since then. Most of these used rectangularly windowed sinewave gratings that varied in width in the direction orthogonal to the bars. A few used circular, square or Gaussian windows. Studies of size effects are consistent in showing that for most spatial frequencies, the threshold decreases as size increases. For small sizes the decrease is rapid, but as size increases the threshold decreases more slowly, appearing to approach an asymptote for large sizes. Using grating patches, Robson and Graham (1981) found an increase in sensitivity out to at least 16 wavelengths in the fovea. There are exceptions to this form at very low and very high spatial frequencies (Pointer & Hess, 1989). Some authors have used two straight line segments to describe the data when plotted on log–log coordinates (Kersten, 1984; Polat & Tyler, 1999).

A Gabor pattern is produced by multiplying a sinewave grating by a two-dimensional Gaussian function. For Gabor patterns the description of experimental results is complicated by the several different measures that are used