Partitioning Mechanisms of Masking: Contrast Transducer versus Divisive Inhibition

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Introduction

The properties of spatial vision mechanisms are often explored psychophysically with simultaneous masking paradigms. A variety of hypotheses have been proposed to explain how the mask pattern utilized in these paradigms increases threshold. Numerous studies have investigated the properties of a particular origin of masking hypothesis but few have attempted to compare the properties of masking at several points in the process. Our study isolates masking due to lateral divisive inhibition at a point where mechanism responses are combined, and compares it with masking of the same target due to a nonlinearity either intrinsic to a mechanism or directly operating on the response of a single mechanism. We also measure the slopes of psychometric functions to examine the relationship between uncertainty and mask contrast.

Studies of simultaneous masking utilizing a pedestal mask (an identical test and mask pattern) have measured facilitation for low contrast masks. This decrease in threshold from the sole target threshold is commonly referred to as the “dipper” effect and has been explained as an increase in signal-to-noise ratio from the high unmasked level occurring as the visual system becomes more certain of target location. The level of uncertainty is indicated by the slope of sensitivity to the target as a function of target contrast in the threshold region.

In these studies, high contrast masks have evoked an increase in target threshold. There have been many theories explaining this threshold increase. Some suggest that masking is the result of an intrinsic nonlinearity within a mechanism or of a contrast nonlinearity that operates directly on the output of a single mechanism. Others put the source of masking at a gain control operation which occurs when a surrounding set of mechanisms divide the response of a single mechanism by their summed response. Still others attribute the masking to noise that is multiplicative relative to the neural response signal, or noise that intrudes on the detecting mechanism from neighboring mechanisms.

A detailed review of this debate is provided by the paper by Klein et al., 2016-02 in this Proceedings.

Threshold elevation functions that show the relationship between mask spatial frequency and masking magnitude cannot illuminate this debate, as we demonstrated at ARVO (1994). For that study, we generated threshold elevation functions (the ratio of unmasked versus masked target threshold) for multi-channel systems using computational models that invoked either divisive inhibition, a set of transducer nonlinearities or multiplicative noise. Threshold elevation functions were indistinguishable when each masking process was assumed to have similar strength. These results led us to design the experiment presented here, which attempts to compare the effects of two of these masking processes, lateral divisive inhibition and nonlinear transducer compression.

Methods

Stimuli produced by Morphonome Psychophysics Software

Figure 1. a) Micro-Gabor test. It is designed to target a simple cell receptive field. It is 2 cycles/degree, 1 cycle at 1/6 bandwidth and a width of 15 surround. b) Pedestal mask. It is identical to the target. c) Annullus mask. Its spatial frequency is 2 cycles/degree. It has 2.5 cycles and its diameter is 25 arcmins. It is 12 times the area of the pedestal test. All stimuli were centered at 3 degrees in the periphery.

Equipment and Stimuli

Stimuli were generated using Morphonome Psychophysics software (Tyler and McBride, 1997). The software was run on a Macintosh Centris (Quastra) 900AV and presented on an Apple Color Display Monitor. A calibration system consisting of the Smith-Kettlewell LightMouse calibration software created a look-up table to linearize the relationship between voltage and screen luminance.

The test was a vertical cosine windowed by a Gaussian $f(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{(x^2+y^2)}{2}}$, where $f$ is the spatial frequency, and $x$ and $y$ the horizontal distance whose 1/6 point, the distance between the center and 1/6 contrast, coincided with 0.5 cosine cycles. This microGabor was balanced in terms of its integrated light and dark regions and was designed to match the single cycle of a simple cell receptive field. In this sense, detection of this test target should be mediated by the most sensitive simple cell matching its profile and lying at the test stimulus location. Any larger receptive field is likely to accrue a higher noise level, and hence be less sensitive to the small test target. However, given the large number of cells responding at each location in the visual field, it may be more reasonable to assume that the stimulus targets a local population of cells with similar orientation, spatial frequency, phase, area, contrast, motion, disparity and color tuning. Nevertheless, the stimuli are designed to make the target population as limited as possible. For example, if there were just 4 cell types along the 3 dimensions, it would take only one cell in each of
the 4x8 locations of this representational space, matching the total number of cells (~64,000) reputed to be in one hypercolumn.

For our experiment, the microGabor test had a spatial frequency of 2 c/deg and was centered at 3 degrees in the periphery. Its width was 15 arc min. The small size of the target at this location in the periphery should ensure that detection is mediated by the most sensitive local receptive field and that the spatial properties of the mechanisms responding to the mask and test are relatively uniform. Contrast was defined according to the Michelson definition, the difference between the highest and lowest luminance points divided by the sum of the highest and lowest points.

There were two mask stimuli, which were both static throughout an experiment. The first, called the pedestal, was a microGabor identical and in phase to the test. Its small size was designed to target the same mechanisms stimulated by the test and thus reveal masking caused by a local contrast nonlinearity in the output function (also known as the contrast transducer function). Note that the microGabor pedestal is unlikely to evoke a significant lateral gain-control masking because the area of the pedestal is only about 1% of the lateral gain-control pooling area measured by Cannon and Fullenkamp (1996). The local contrast nonlinearity could be a compressive operation within the mechanism or operating on the output of a single mechanism. Such a compression could be due to an instantaneous output nonlinearity or local feedback gain control within the path of the individual mechanism. It is difficult to distinguish these possibilities unless the gain control has a slower time course than the direct signal pathway. Or, finally, the nonlinearity could be due to the intrusion of contrast-correlated noise from cells stimulated by the pattern. The point is that the pedestal will target masking generated by a process very local to the detecting mechanism. It should not invoke divisive inhibition from lateral cells because the stimulus is small relative to any conceivable spatial gain pool.

The second type of mask was an annular cosine grating, and an inner radius equal to twice the 1/e bandwidth of the test and an outer radius equal to twice the inner radius. Thus, the microGabor contrast fell to a thin ring of gray before reaching the inner radius of the annulus. The orientation, spatial frequency and phase were identical to that of the test. Since there was no coincident mask, the annulus should not generate transducer masking in a cell whose receptive field matched the form of the microGabor. The large area of the annulus (12 times the area of the microGabor) should stimulate many nearby cortical cells, providing strong input for a lateral divisive gain pool.

Procedure

The male and female observers fixated binocularly at a white fixation box, located at 3 degrees to the left of the stimuli. They were instructed to shift their gaze within this box, to prevent adaptation to the phase of the stimuli. Both observers had normal vision with the use of glasses.

A temporal two-interval forced-choice procedure was used to measure a five-point psychometric function for each mask condition (figure 2). An alert beep chimed at the beginning and end of each presentation interval. The luminance of the test was modulated according to a raised cosine whose cycle length was 600 msec or 300 msec at half height. The mask was continuously presented and the interstimulus interval was 400 ms. In the rare case of a distraction, the observer had the option of repeating a trial. Two-Interval forced-choice provides a measurement of the proportion correct, however we are interested in the psychometric (d') functions. The proportion correct corresponds to the probability of response to the signal + noise being greater than the probability of response to the noise on any trial. Assuming that both functions are Gaussian with equal variance, the proportion correct distribution is equal to the difference between the response probability to the signal + noise and the response probability to the noise, which in turn is Gaussian with the same standard deviation multiplied by V2. So, for 2AFC, P = cunnorm(d'/V2) and d'(P) = V2 inverse cunnorm(P). (See Harman, 1977, for a discussion of 2AFC).

The psychometric functions were fit with a power function at contrasts close to threshold combined with a linear function at contrasts much beyond threshold. The intersection was constrained to be continuous. Contrast increment threshold is defined in this study at a d' equal to one, which corresponds to 77% proportion correct.

Temporal two-alternative forced choice
The target randomly appears in one of the two intervals.

Results

As discussed in the introduction, the purpose of this study is to examine the junctures in pattern processing where masking is generated. Masking generated by an intrinsic nonlinearity local to the detecting visual mechanism or operating on the output of a single visual mechanism will produce masking in the pedestal set-up, but not in the annulus set-up. Lateral masking generated by the pooled response of many mechanisms, divisively operating on the response of the most sensitive mechanism, will generate masking in the annulus set-up, but not in the pedestal set-up. Masking generated by increased noise, because spatial and/or phase uncertainty forces the visual system to monitor the activity of multiple pattern analyzers, will be indicated by a steepened psychometric function.
Figure 3: Increment detection threshold as a function of pedestal mask contrast in contrast threshold units (ratio of the measured threshold to the absolute threshold). The curves follow the classic 'dipper' shape with the dipper representing the facilitation at low pedestal contrasts. Least square regression lines (excluding absolute threshold) show slopes of 0.29 and 0.23 for observers AGS and LBS, respectively. These are significantly lower slopes than for the local pedestal mask. Note: The absolute threshold, corresponding to zero pedestal contrast, is placed at 0.5 pedestal contrast for plotting purposes.

Figure 4: Increment detection threshold as a function of annulus mask contrast. No facilitation was measured. Least square regression lines (excluding absolute threshold) show slopes of 0.39 and 0.38 for observers AGS and LBS, respectively. These are significantly lower slopes than for the local pedestal mask. Note: Again, the absolute threshold, corresponding to zero pedestal contrast, is placed at 0.5 pedestal contrast for plotting purposes.

Increment detection threshold as a function of mask contrast (TVC curves) are shown in figures 3 and 4. The TVC for the local pedestal (figure 3) follows the classic 'dipper' shape with the dipper representing facilitation at low pedestal contrast. This behavior is what we expect if uncertainty or an accelerating nonlinearity at low contrast were generating masking. The function at high levels of pedestal masking increases with an exponent of about 0.6, similar to that reported by Legge and Foley. It is important to note that the masking measured in this case is due to a nonlinearity local to the detection mechanism. It is not produced by lateral gain control.

The relationship between annulus contrast and test increment detection threshold is illustrated in figure 4. No facilitation was measured in this configuration. The logarithmic slope of about 0.3 for both observers is significantly weaker than the masking generated by the local nonlinearity in the local pedestal. To illustrate the behavior of uncertainty in this paradigm, we show the psychometric functions for observer AGS in figure 5. The psychometric functions for observer LBS in figure 5 were similar.
Psychometric Functions for Annulus Mask

Figure 5: Series of 5-point psychometric functions for observer LBS measured with the annulus mask. The slope of the psychometric function provides a gauge of the level of channel uncertainty. The roughly constant slope of -2 of two suggests only a moderate level of uncertainty is operating at all mask contrasts.

The gradient of detection as a function of increment threshold indicates the level of channel uncertainty. If there were zero uncertainty, where the observer had perfect information about the location and spatial tuning of the channel best stimulated by the target, the psychometric functions would have a slope of one. As shown in figure 5, the slopes of the functions were around 2 at all mask contrast levels. Since uncertainty appears to remain constant as masking increases, it is evident that changes in uncertainty are playing a minimal role in the measured masking effect. There are at least two other ways to interpret this masking of detection sensitivity. One is that the attention strategy is unaffected by the presence of the mask in this peripheral stimulus location and the threshold increase is due to lateral gain control. The alternative hypothesis is that the fixed level of the (invariant) psychometric slopes is explained by the idea that the observer has an inherent degree of uncertainty about the target position in the periphery that prevents the attention mechanism from focusing on the target. If there is noise correlated with the annulus contrast, the annulus produces a masking effect by raising the noise level against which detection is made.

Conclusion

The results of this study suggest that masking can be generated at least three points in the visual processing stream, depending on the configuration of patterns contiguous to the target. The increase in sensitivity near threshold implied that uncertainty or an accelerating transducer at low contrast has influenced detection, but only for the identical local pedestal. By the term “transducer” we mean the nonlinear aspects of the near threshold local processing, excluding variation in slope due to uncertainty.

Acknowledgments

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References