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Contrast Sensitivity Functions for Analysis and Simulation of Visual Perception

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The response of visual filters has been used to simulate vision and to design image enhancement techniques for the visually impaired. For the simulations and enhancements to be useful, they must be based on appropriate measurements of the filters being studied. Most previous measurements of spatial contrast sensitivity functions (CSFs) have been based on stimuli that give maximal contrast sensitivity. We measured CSF using stimuli that are better suited for analyzing perception of images. Use of the different types of CSF yields notably different simulations.

Measurements of maximal threshold sensitivity may enable earlier detection of visual loss. Extended grating stimuli are also convenient for experiments where global Fourier analysis is used to interpret results. However, extended grating CSFs may be inappropriate for simulation of vision in normals (Ginsburg, 1978) and low vision patients (Lundh et al., 1981; Peli et al., 1989) and for the design of image enhancement techniques as visual aid (Peli & Peli, 1984; Lawton, 1988).

Repeated, continuous cycles at any frequency are rarely seen in natural scene images. Only when periodic patterns (such as a picket fence) appear in the image does one find more than two consecutive high-contrast cycles anywhere within the images. Thus, the sensitivity added by spatial summation is unlikely to be representative of visual perception of images other than gratings. The use of localized stimuli matched to the impulse response of simple cortical cells is a natural way to obtain "valid" CSFs that minimize spatial summation.

The temporal presentation of the gratings is usually a gradual fade-in and -out rather than flash-on and -off, as the former presentation results in increased threshold sensitivity measure. In free viewing, saccadic eye movements result in abrupt changes of eye position. Thus, the local presentation of stimuli to receptive fields usually does not follow the gradual fade-in and -out presentation. Therefore, thresholds measured with abrupt presentation of grating patches better represent the perception of localized contrast in complex images.

Detection thresholds are commonly measured using paradigms in which only the presence of the target is recorded, without need for the subject to perceive any aspect of form, such as orientation, profile, or contrast. This often produces the lowest threshold, but does not necessarily correspond to the information required for useful image interpretation. For this purpose the experimental task should include some form discrimination.

In view of the above arguments, we designed our CSF measurements to be used for low vision simulation and image enhancement based on visual loss in the following way: Stimuli presented were patches of sinusoidal gratings in a Gaussian envelope (Gabor functions) of 1-octave bandwidth, flashed on for 1 sec at either horizontal or vertical orientation, and abruptly removed. We compared the CSF obtained with these stimuli to the data obtained with fixed size screen, narrower bandwidth (more cycles), and gradual temporal presentation. Simulations of the appearance of images to normal observers, using different types of CFSs measured, are used to demonstrate the effect of these differences.

Methods

Stimuli were generated with an Adage 3000 image processor using 10 bit digital-to-analog converters on a Tektronix 690SR, 60Hz noninterlaced monitor. The Gabor function type stimuli were composed of horizontal or vertical sinusoidal grating in cosine phase, multiplied by a 2-dimensional Gaussian envelope. The 1-octave stimuli contained $12/\pi \cong 4$ cycles; however, only about 2 cycles are visible due to the rapid decline of the envelope. The additional cycles were used to avoid sharp terminations of the stimuli. The narrower bandwidth stimuli of 0.5, 0.25, and 0.125 octave contained about 4, 8, and 16 visible cycles, respectively. Fixed screen stimuli were adjusted to $2.7° \times 2.7°$. The surrounding screen luminance was matched with the mean luminance of 46 cd/m^2 for all presentations.

Stimuli were represented in a 2-alternative, forced-choice paradigm. Seven spatial frequencies (0.5-10 cycles/deg) were randomly interleaved. Contrast was changed in 0.1 log unit steps. After the subject signalled readiness by pressing a button, a grating patch was presented. The subject then indicated whether the grating patch was horizontal or vertical and received auditory feedback. The psychophysical procedure was a hybrid method that consisted of 3 steps, starting with a staircase procedure. After the second reversal of direction, the procedure was changed to a modified parameter estimation by sequential testing (PEST) (Lieberman & Pentland, 1982). Although the stimulus presentation continued to be controlled by the staircase procedure, the data were collected and analyzed by the PEST algorithm. Finally, when an initial threshold estimate was determined by the PEST routine to be within confidence interval of 40%, stimulus presentation control was switched to PEST. This modification prevented long random walks that may occur at the beginning of a PEST routine (Klein & Manny, 1989). With this method, 50-80 presentations were required to reach the termination criterion. A psychometric function was then fitted to the data to obtain threshold estimate and standard deviation (on the order of 0.1 log unit).

Fifteen normal young subjects were tested using both 1-octave patches and standard fixed-screen stimuli. Five of the subjects also were tested with narrower bandwidth patches (of 0.5, 0.25, and 0.125 octave) and with both flashed and gradual temporal presentations.

Simulations of the appearance of images spanning 2° of visual angle were performed using the two CSFs illustrated in Fig. 3. The simulations were based on a pyramidal structure of local band-pass filtered contrast (Peli & Goldstein, 1988). The images were sectioned in the frequency domain into 1-octave bandwidth sections. Contrast at each spatial position was calculated by dividing the band-pass filtered value by the low-pass filtered value at the same point. At each level of the pyramid, every point was compared with the appropriate contrast threshold for this level. If the contrast at that point was higher than the threshold, the amplitude of this point was not affected. If the contrast was below the threshold, the amplitude was set to zero. The same method was recently used to illustrate the effect of image enhancement on the appearance of images for low vision patients (Peli et al., 1989).

Results

The CSFs recorded from the normal subjects using the 1-octave patch and standard fixed-screen stimuli are presented in Fig. 1. For all subjects, there were important differences between the patch and the extended grating CSFs. The latter was a band-pass function peaking at about 4 cycles/deg, while the patch CSF was low-pass. The patch sensitivity was 0.5 to 1.0 log unit lower over the entire spatial spectrum.

Fig. 2 illustrates the CSFs of one of the subjects tested with wider patches (narrower bandwidth), with both the abrupt and gradual temporal presentations. Results with 0.125 octave were almost identical to results

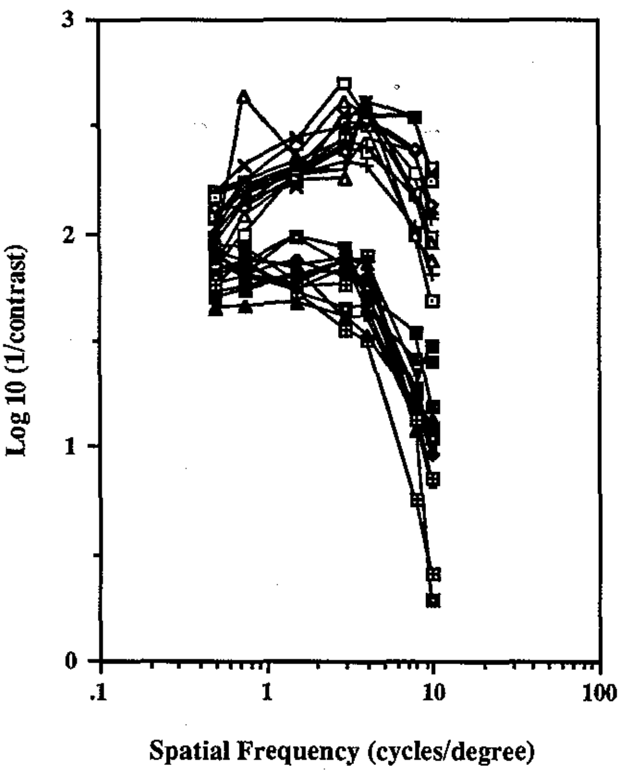

Fig. 1. Contrast sensitivity function of 15 normal young observers. Upper curves, CSF measured using standard fixed screen (2.7° x 2.7°) with flash-on, flash-off presentations. Lower curves, CSFs measured from the same subject using a Gabor patch of 1-octave bandwidth gratings.

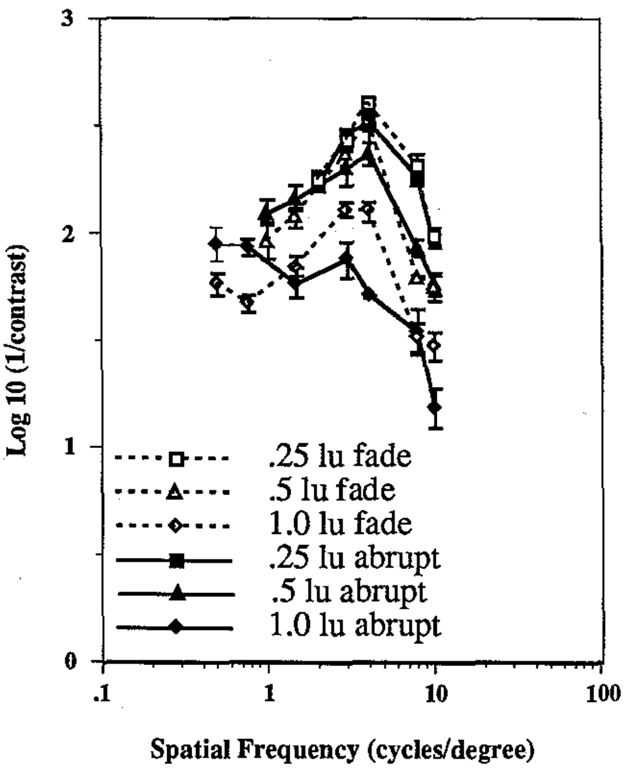

Fig. 2. Effects of changing bandwidth and temporal presentation on measurement of patch CSFs. Solid lines and filled symbols, abrupt flash-on, flash-off. Dashed lines and open symbols, gradual presentation.

with 0.25 octave and were removed for clarity. The functions changed gradually from low-pass to band-pass characteristics as the number of cycles were increased, and there was a corresponding increase in sensitivity. The difference between the abrupt and the gradual temporal presentations was small for the narrower bandwidth cases. The pass band of the gradual presentations was slightly narrower than those of the abrupt presentations. For the case of the 1-octave patch, the gradual presentation resulted in significant increase in sensitivity at the intermediate frequencies of 3 and 4 cycles/deg. In all 5 cases, at the lowest tested spatial frequency of 0.5 cycle/deg, the sensitivity to the gradual presentation was actually lower than to the abrupt presentation. Thus, the change with increasing number of cycles represents increased sensitivity at intermediate frequencies. For all bandwidths tested, the gradual temporal presentation resulted in sharper band-pass characteristics with increased sensitivity at intermittent frequencies and decreased sensitivity at low and high frequencies.

The important effect of using different contrast sensitivity functions on the simulation of visual perception of faces is illustrated in Fig. 3. If the contrast sensitivity function obtained with the standard fixed screen presentation is applied to simulate the appearance of a face spanning 2° of visual angle, only features at spatial frequencies higher than 15 cycles/face will be eliminated. This will result in a very small change in the image. However, if the contrast sensitivity obtained with a patch of 1-octave bandwidth is used, image content above 6 cycles/face will be affected, resulting in blurring of most fine details.

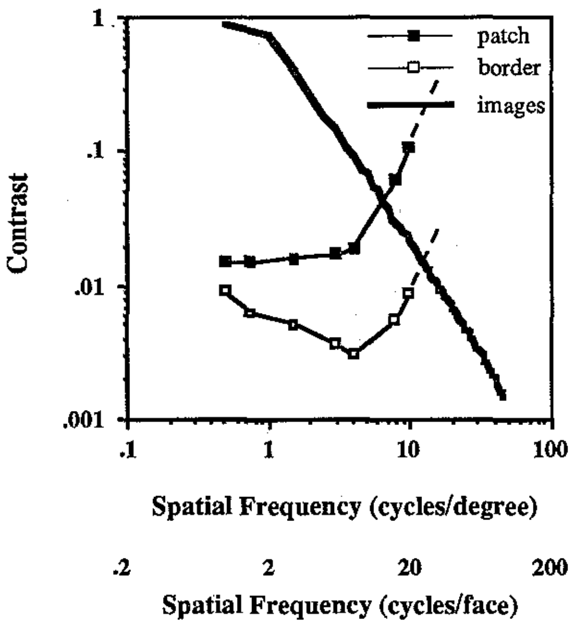

Fig. 3. Mean contrast detection thresholds recorded with fixed-size screen compared with thresholds recorded with 1-octave Gabor patches. Dashed lines, extrapolation to 16 cycles/deg. Thick solid line, radially averaged contrast spectra of 5 difference faces. Spatial frequencies (in cycles/face) are visible up to the point of intersection with the contrast threshold functions and are invisible for spatial frequencies beyond the point of intersection.

The results of simulations using the 2 difference functions are illustrated for face and street scene in Figs. 4 and 5, respectively. In both cases, the images obtained with the CSF measured with the patch of 1-octave bandwidth results in substantial filtering which more accurately represents the perception of the original images when they span 2° of visual angle.

Discussion

Extended grating stimuli are usually presented on a fixed-size screen, resulting in a varying number of cycles with the change of spatial frequency. Recorded thresholds depend on spatial summation over the responses of multiple spatially localized mechanisms or receptive fields. Therefore, the size of the fixed screen is usually adjusted to permit more than a critical number of cycles at the lowest spatial frequency tested (Estevez & Cavonius, 1976).

Standard methods of estimating CSFs frequently yield very high levels of sensitivity (300 at the peak). They are liable to be representative of actual contrast sensitivity in free viewing of daily images, due both to the local nature of natural contrast and to temporal transients originating from eye movements. The ratio of abnormal CSF to the normal sensitivity function is commonly used both for simulating low vision (Lundh et al., 1981) and for calculating compensatory filters for image enhancement. The exact method used to obtain the CSF may not affect that ratio substantially. For example, Hess & Howell (1978) showed that the ratio of normal to abnormal CSF is not affected by field size (number of cycles). The use of such ratios represents the application of linear system analysis to the visual system, which is known to be highly nonlinear. For example, suprathreshold contrast is perceived centrally and peripherally nearly equally, while the contrast threshold changes significantly. In simulation of such a nonlinear system, knowledge of the absolute threshold is required. Linear analysis may be justified only in a few cases, such as cataracts in which an optical linear filter affects the system response. The 1-octave bandwidth Gabor type patch that we have used may be a better stimulus for measuring such a perceptually valid CSF by addressing the local nature of contrast in images, as well as at the temporal presentation, and by requiring form discrimination.

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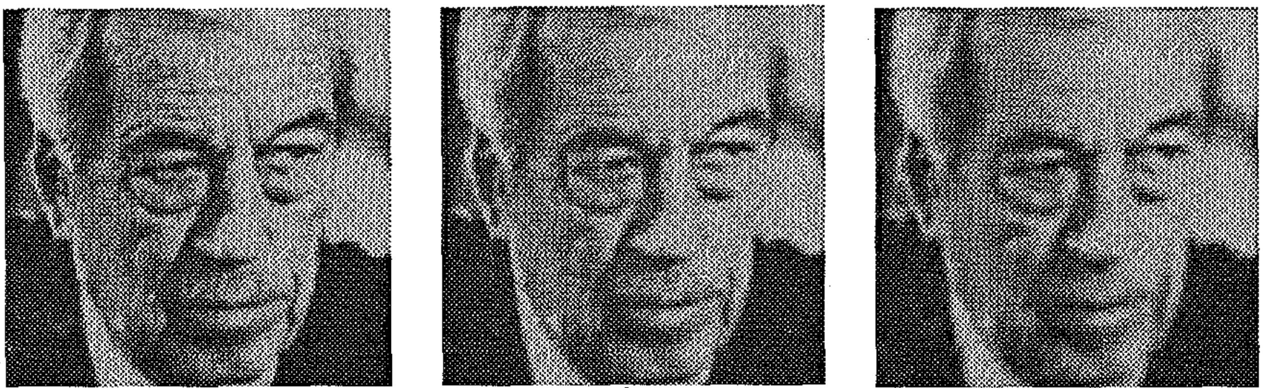
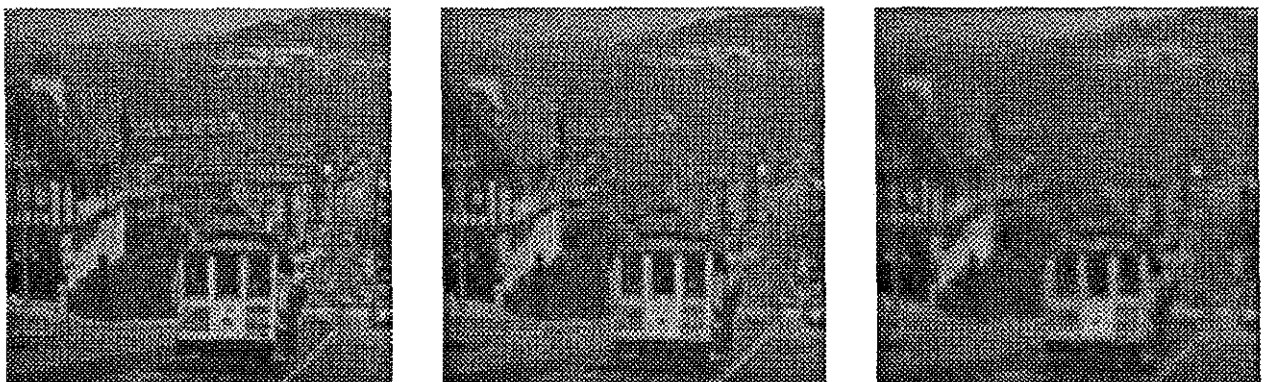


a b c

Fig. 4. Simulation of appearance of face image. a, Original images. b, Image in "a" processed using the CSF measured with fixed screen to simulate appearance if it spans 2° of visual angle. c, Same as "b" but using CSF measured with 1-octave patch stimuli.



a b c

Fig. 5. Same as Fig. 4 for a scene that contains more information at higher spatial frequencies.

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