ACTA NEUROBIOL. EXP. 1988, 48: 283-293

APPARENT CONTRAST OF SPATIALLY AND TEMPORALLY SAMPLED GRATINGS

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Key words: human vision, contrast perception, Fourier analysis, spatial sampling, temporal sampling

Abstract. We have measured the apparent contrast of spatially and temporally sampled gratings having the spatial frequency of 2, 4 and 8 c/deg. A contrast matching task was used in two different sampling conditions which allowed us to stimulate selectively the sustained and transient mechanisms in spatial and temporal vision. The results demonstrate the visual interpolation characteristics in the two domains and suggest a better response linearity for spatial than for temporal interpolation. The strongest nonlinear responses were obtained for temporally sampled medium spatial frequency gratings, suggesting separate temporal processing mechanisms for medium and high spatial frequencies.

INTRODUCTION

Our ability to recognize fragmented visual objects is based on the visual system's capacity to reconstruct the representations of complex objects from surprisingly little information. This is also true for tasks that require high resolving power and effective sampling characteristics of foveal vision. The visual resolving power in the so called hyperacuity tasks, for example, can be of the order of a few seconds of arc (1) which is less than the sampling interval of the human foveal cone lattice i.e., about 30 s of arc (2). Without effective spitial integration of image features, such a performance would not be possible.

We have studied the visual reconstruction or interpolation capacity of human spatial and temporal vision by measuring the amount of visual interpolation of sampled grating targets. Mathematically, ideal interpolation is equivalent to low-pass filtering and psychophysically, an estimate of the interpolation strength can be derived from contrast match experiments. The matching does not, however, allow the estimation of the exact form of the underlying interpolation functions.

When a spatial signal, e.g. a grating, is sampled in space or in time, some of the original information is lost. Because the visual system has characteristic impulse responses for spatial and temporal stimulation, its responses to spatially or temporally sampled stimuli would be expected to reflect the nature of these different mechanisms. By using delta sampling and pulse sampling schemes it was possible to separate the mechanisms sensitive to smooth and abrupt (edges) features in the stimuli, either in space or in time.

METHODS

Stimuli. The grating stimuli were generated on the face of a Joyce cathode ray tube having a white (P4) phosphor with a linear luminance response and the frame rate of 100 Hz. The stimulus field dimensions were 20 cm × 20 cm and the number of raster lines was 512. The mean luminance of the display was 120 cd/m^2. Viewing was monocular and from the distance of 912 cm.

The experimental stimuli were sinusoidal and square wave gratings (2, 4, and 8 c/deg) that were sampled in time or in space. In spatial sampling, the gratings were produced by selecting every n-th vertical raster line of the grating for presentation and setting the raster lines between the sample lines to the mean luminance value which was always 120 cd/m^2. This is here called sampling (DS) for which the sampled sinusoidal grating had the following luminance profile:

$$L_s(x) = L_o\left(1 + m\sum_{i=1}^{512}\sin(2\pi fx)\,\delta(x - idx)\right),$$

where $L_s(x)$ is the luminance of the grating at the horizontal location x, m is the Michelson contrast (L max-L min)/(L max + L min), f is the spatial frequency in c/deg, dx is the separation between the sample lines, and $\delta(x - idx)$ is the delta sampling functions which is zero outside the sample points idx. The peak-to-peak contrast of the original sinusoidal grating from which the samples were taken was 0.64 and that of the square wave was $(\pi/4) \cdot 0.64 = 0.50$ so that the fundamental component of the square wave was equal to the corresponding sine wave in the experiments.

The sampling energy could be increased by increasing the number of consecutive sample lines per each cycle of the sampling waveform while the sampling frequency was kept constant, i.e. by using a pulse train instead of an impulse train for the sampling. This is here referred to as pulse sampling (PS). For sake of clarity, these different sampling schemes have been referred to by the ratio s/ns where s is the number of consecutive sample lines shown i.e., the width of the sampling pulse, and ns is the number of consecutive lines set to the base luminance value. In effect this kind of sampling is equivalent to the sampling of a signal and then adding a constant to prevent negative luminance values from occurring.

In temporal sampling, the duration of each stimulus frame on the display was 10 ms which was used as the time unit of temporal sampling. Different sampling rates were produced by presenting the grating for n x 10 ms and by setting the display luminance between the sample presentations to the mean value. Therefore, both spatial and temporal sampling had formally similar spectral contents.

Psychophysical task. The task of the subject was to adjust the contrast of a continuous comparison grating until its contrast appeared equal to that of a sampled standard grating. In the sampled grating, the sample lines were visible, of course, but also a visually interpolated waveform could be seen as if it were located behind the sample lines. The contrast of this "waveform Gestalt" was matched against the continuous grating. The task was performed under the control of a computer-driven adaptive up-and-down algorithm. The matching task was repeated with different sampling rates and duty cycles of the sampling waveform. For example, the widest sampling pulse was such that for each cycle of the sampling waveform, 15 consecutive sample lines of the grating were shown and 1 was set to the base luminance (the whole grating consisted of 512 vertical, luminance modulated lines each of which had an approximate width of 15 s). A complement to this was the case of delta sampling when only 1 sample line represented the original signal and 15 consecutive raster lines were set to the base luminance. Similar procedures were used in both temporal and spatial sampling.

Three subjects participated in the experiments and they all had normal vision.

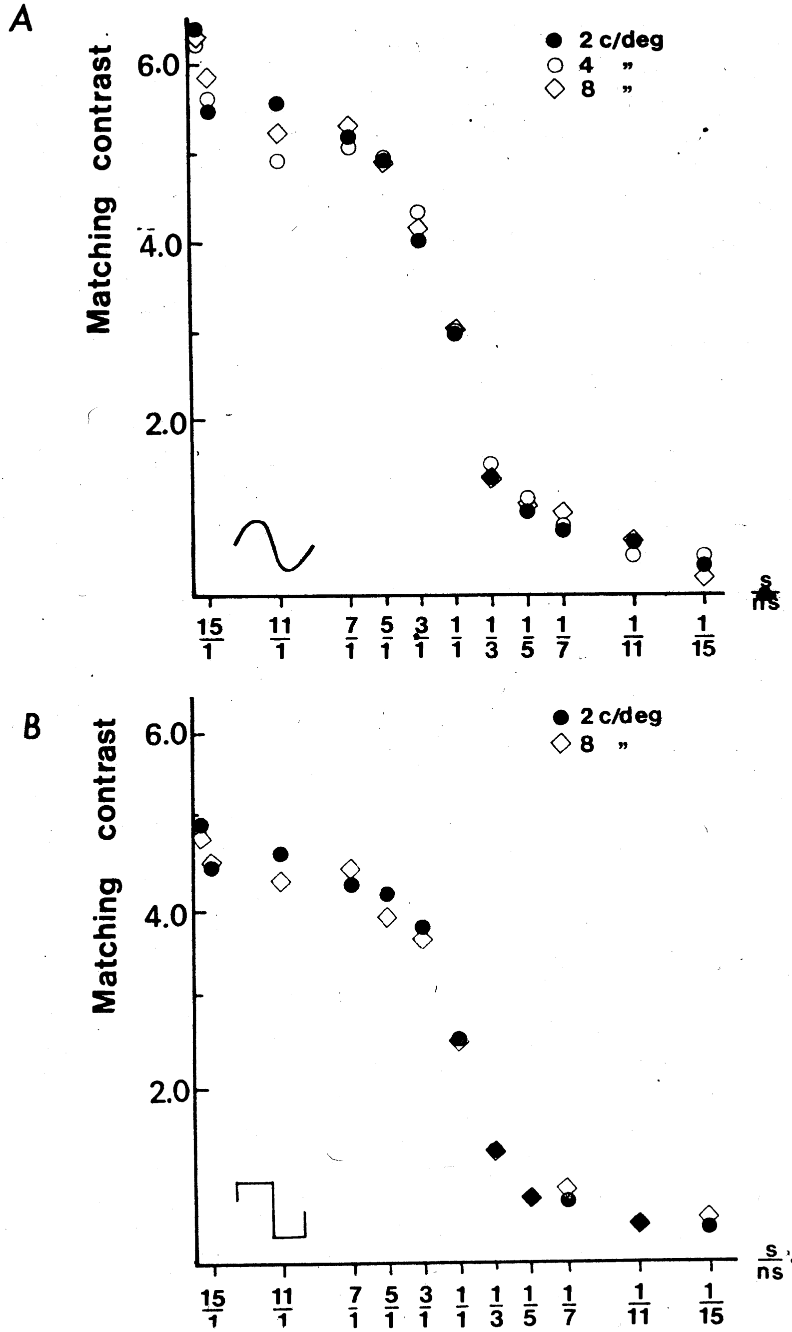

Fig. 1. *A*, the apparent contrast of sampled sinusoidal gratings. The abscissa shows the ratio s/ns describing the duty cycle of the sampling waveform. The number of spatially consecutive sample lines taken from the original waveform is given by s and ns is the corresponding number of lines set to the base luminance value. The ordinate describes the contrast of a continuous spatial sinusoid that was perceptually equal to the contrast of the sampled grating. The matching data are very

RESULTS

Apparent contrast of spatially sampled sinusoidal gratings. The sinusoidal gratings were sampled with two complementary sampling schemes, delta sampling (DS) and pulse sampling (PS). The sampling pulse trains are shown as insets in Fig. 3. When a sinusoidal signal is delta sampled, the energy of its fundamental frequency component increases as a function of the sampling frequency (samples/deg) applied whereas for the type of pulse sampling we used, it decreases with the sampling frequency.

The results of the contrast matching experiment with sampled sinusoidal gratings are shown in Fig. 1*A*. The contrast value of the continuous sinusoidal grating that appeared equal to the contrast of the sampled grating is shown on the ordinate. On the abscissa, the ratio s/ns (s = number of consecutive samples; ns = number of consecutive samples given the base luminance value) describes the sampling conditions used. Hence, the sampling frequency is proportional to $1/(s + ns)$. The use of the ratio s/ns results in a nonlinear abscissa and to make the analysis of the visual system's contrast response more feasible, the data have been scaled and expressed as a function of the sampling rate in Fig. 3 together with the data from temporal sampling.

As can be seen from Fig. 1*A*, the results for all three spatial frequencies of the sinusoids are almost identical when expresed as a function of the s/ns ratio suggesting that there is no significant difference between the interpolation processes used by the visual system for higher and medium spatial frequencies. This is also true for the two spatial frequencies of the square wave gratings studied (Fig. 1*B*). Because the peak-to-peak contrasts of the two original waveforms from which the samples were taken were such that the fundamental frequency components were the same in both waveforms, the absolute matching contrasts were mostly higher for the sinusoidal gratings. However, for small values of *s/ns*, i.e., delta sampling, the matching contrasts were almost identical for both waveforms and corresponded well to the energy of the fundamental component of the sampled sinewave. This suggests the possibility that delta sampling might produce a relatively stronger interpolation of the sampled square wave than the pulse sampling does.

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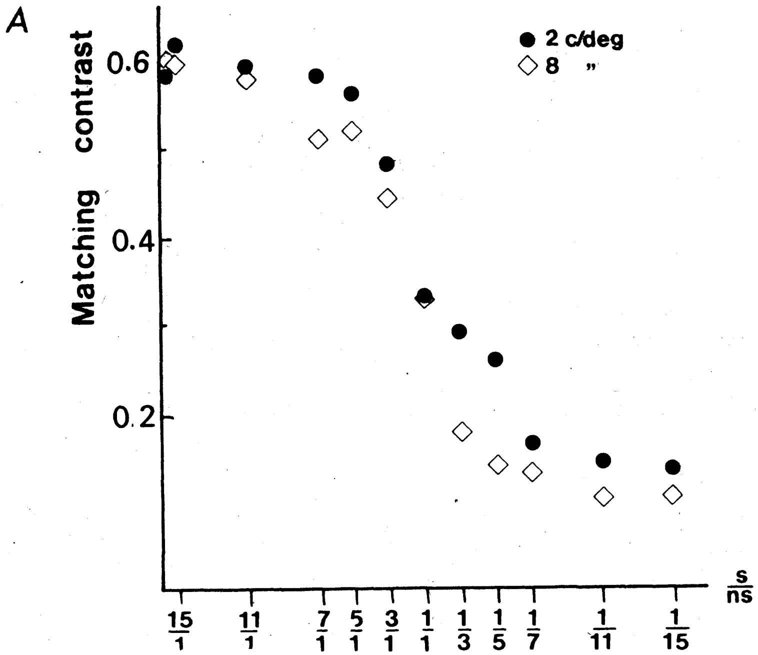
similar for all spatial frequencies studied suggesting the operation of a similar interpolation mechanisms at these spatial scales. *B*, the same experiment but with square wave gratings in which the fundamental component was the same as in the previous sinusoids. The general trend is very similar for both waveforms but at lowest values of the s/ns ratio the perceived contrast of the sampled square wave gartings is relatively enhanced. Subject T. R.



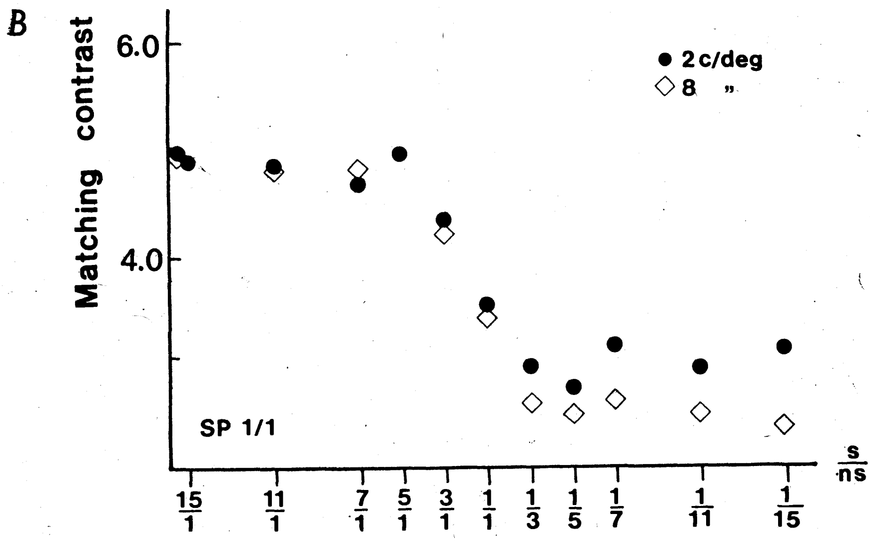


Fig. 2. *A*, the apparent contrast of a spatially continuous sinusoidal grating that was sampled temporally by presenting the grating as a train of flashes. The apparent contrast of these gratings follows a similar function of the sampling ratio as was shown for spatial sampling. The data for the two spatial frequencies are clearly different showing a contrast enhancement of the lower spatial frequency (2 c/deg). *B*, The same experiment except that now the grating was both spatially and temporally sampled. The temporal sampling parameters are shown on the abscissa as in 2 *A*. SP 1/1 indicates that every other raster line represented the original sinusoidal waveform and the lines between them were set to the base luminance value. The lower spatial frequency is again enhanced by low s/ns ratios. Subject T.R.

Temporal sampling. In the next experiment the same contrast match task was used but now temporal sampling was applied by presenting a sinusoidal grating as flahes of variable duration that alternated with a constant luminance background. The subject had the task to match the perceived contrast of the temporally sampled grating against a temporally continuous waveform. The results of this temporal sampling of a spatially continuous sinusoid are shown in Fig. 2*A*. The overall results were similar to those of the previous experiment using spatial sampling but with one clear exception. For the temporal delta sampling, i.e., for small values of *s/ns* ratio, the perceived contrast of the lower spatial frequency (2 c/deg), spatially continuous sinusoid was systematically above that of the 8 c/deg grating. The standard deviations of the matches were typically less than 3% suggesting that the observed differences are statistically highly significant.

Figure 2*B* shows the temporal sampling data for a sinusoidal grating that was sampled also in space by taking every other raster line for presentation and by setting the others to 120 cd/m^2. The physical effect of this spatio-temporal sampling is to attenuate the signal contrast in proportion to the sampling rate used in both domains. However, there is again a clear tendency for the temporal delta sampling to enhance the perceived contrast of the 2 c/deg grating more than that of the higher spatial frequency. This suggests a better responsivity of the medium spatial frequency channels to the temporal transients.

Asymmetry in the visual effects of spatial and temporal sampling. The results from the spatial sampling experiment and those of the temporal sampling have been combined in Fig. 3 where the relative matching contrast is shown on the ordinate as a function of the sampling rate and the type of sampling used. For the temporal domain the sampling rate is given in Hz which describes how many cycles of the sampling waveform occurred per second. Notice that the sampling waveform was used to multiply the original signal waveform but not its dc component. For spatial sampling, the sampling rate gives the number of sampling waveform cycles per one degree of a visual angle. To make the comparison between spatial and temporal sampling easier the matching contrast has been expressed in relative units. The relative matching contrast was calculated by dividing the obtained matching contrast by 0.64 which was the mean of several matches made to a spatially and temporally continuous test grating.

The representation shown in Fig. 3 makes it possible to demonstrate some of visual consequences of the spatial and temporal sampling schemes. Firstly, the contrast matches predicted from a simple physical calculations of the sampled waveform contrast have been shown by the straight broken lines that form the sides of the rectangle. In the case of a linear relationship between the sampling rate and perceived contrast, we would expect the data points to fit the four predicted lines. Secondly, the four different quadrants represent diffrent stimulation situations which have been indicated in the figure.

For example, sustained spatial and temporal stimulation was dominant when several consecutive line samples (in space) or stimulus frames (in time) were presented and only one interleaving sample line or

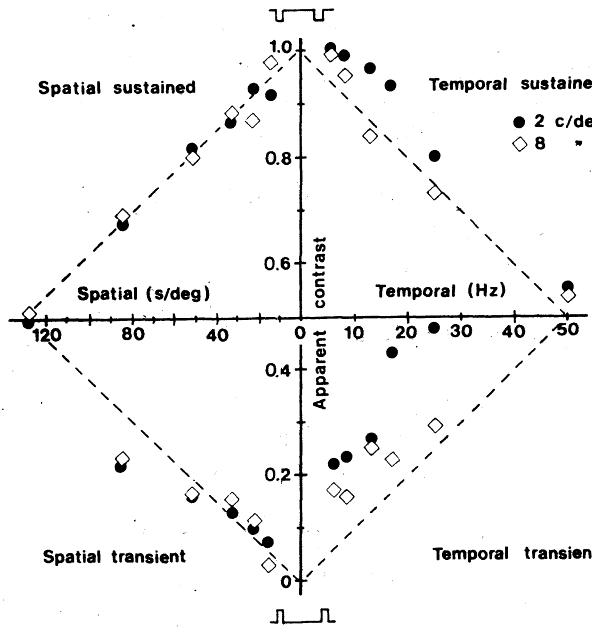


Fig. 3. The apparent contrast of spatially and temporally sampled sinusoidal gratings. Combined data from the spatial and temporal sampling experiments shown in Fig. 1. The sampling waveforms used have been schematically shown as the insets. The upper part describes the pulse sampling data and the lower part the delta sampling data. The broken lines forming the sides of the square show the average physical contrast remaining in the sampled grating. The four quadrants represent the four different stimulation situations. For a detailed explanation, see the text. Two different spatial frequencies, 2 c/deg and 8 c/deg. For spatial sampling of both sampling types the data fit rather well to the predicted values. However, in temporal delta sampling there occurs a significant nonlinear contrast enhancement at intermediate sampling rates.

a frame was set to the base luminance value. Spatial and temporal transients dominated when only one sample value per each cycle of the sampling waveform was shown and several consecutive values in space or in time were set to the base value.

In all quadrants of this representation except one, the data fitted relatively well to a linear function and the correlations of the linear regression fits varied between 0.973 and 0.997. In spatial sampling there were no systematic differences between the three spatial frequencies. However, in temporal sampling the lower spatial frequency (2 c/deg) showed some enhancement of the perceived contrast at the lowest temporal sampling rates.

The general trend of the results of the temporal sampling experiment is clearly different from its spatial equivalent. Especially in the case of delta sampling (lower right quandrant), the two spatial frequencies have a different dependence on the sampling rate (Hz) used. There the matching contrast follows a strongly nonlinear function of the temporal sampling rate applied. This enhancement effect is strongest at about 10-15 Hz and it is especially strong for the 2 c/deg grating suggesting that it is a general property of the lower or medium spatial frequency mechanisms. For comparison, in the temporal pulse sampling (upper right quadrant) the decrease in apparent contrast follows a more or less linear function of the temporal sampling rate.

We can assume that at low temporal sampling rates the delta sampling stimulates mainly the transient temporal mechanisms because the sustained mechanisms are not fast enough to respond to the delta stimulation. On the other hand, the sustained mechanisms are able to follow the pulse sampled stimuli on which the transient stimulation is only briefly superimposed. From this point of view, it is interesting to note that when the transient system is stimulated at a rate of about 10-15 Hz, it produces a strong nonlinear contrast enhancement. However, this nonlinear effect seems to be relatively independent of the sustained temporal mechanisms because the transient stimulation does not affect the contrast response to the pulse sampled stimuli at the corresponding temporal frequency range.

DISCUSSION

By using spatially and temporally sampled gratings, we were able to investigate the visual system's capacity to integrate simple spatial signals in space and time in functionally analogous situations. In general, the results show that the spatial sampling noise does not mask the visual system's contrast response as the perceived contrast of spatially sampled gratings could be predicted fairly well from the physical energy left in the sampled gratings. This was true for both high (8 c/deg) and medium frequency (2 c/deg) gratings.

At very low spatial delta sampling rates the perceived contrast of the square wave gratings was somewhat enhanced in comparison to the sine waves. This is in accordance with the finding that the square wave gratings tolerate undersampling better than the sine waves (3). The reason for this selectivity is not known even though the edges seem to carry significant information for the visual reconstruction of the sampled signals.

Because we used two different sampling strategies for our stimuli, the so called transient and sustained visual mechanisms could be selectively stimulated in both spatial and temporal domains. When single, regularly spaced lines or 10 ms stimulus frames were dropped off from the stimuli, the sampling was assumed to activate predominantly the sustained spatial and temporal mechanisms. In such cases the spatial sampling resulted in a perceived contrast that rather well corresponded to the physical contrast remaining in the grating. In temporal sampling this correspondence was not as good and the perceived contrast of the low spatial frequency gratings was more enhanced than the higher frequency. This was typical at temporal sampling rates of about 10-20 Hz. This corresponds to the flicker rate at which modulation thresholds are typically lowest (4,5). It is also in accordance with the finding that the perceived contrast enhancement for flashed gratings is strongest for low spatial frequencies. Typically the enhancement has been found highest at the exposure durations of 80-100 ms (6) which corresponds to the sampling rate of 10 Hz or more.

The overall results show that in some conditions the visual system is able to interpolate between the signal samples so that the perceived contrast of the waveform approaches the value measured for continuous stimuli. This suggests that the neural interpolation processes involved must be such that the signal contrast can be preserved. One candidate type of filter having such a property is the ideal interpolation function that has the form sin x/x. For the visual system, more realistic interpolation functions can be formed of the difference of Gaussians (7) or other similar functions which have been used to model the sensitivity of the visual system to complex spatial patterns. We have not, however, tried to find the optimal interpolation function for our data.

The origin of the contrast enhancement that was produced by temporal delta sampling is not known but it seems reasonable to assume, as has been done for threshold vision, that it is caused by a temporal summation within the spatial channels stimulated (8). Only at temporal sampling rates that were high enough for the Talbot-Plateau law to hold (at fusion rate), the perceived contrast of a spatio-temporally sampled grating could be kept constant by keeping the product of spatial and temporal sampling rates constant. The definition of the spatial fusion requency is not straightforward, however, because in a spatially sampled grating, the continous waveform Gestalt is visible even when the individual sample lines are still seen. In other words, spatial fusion can take place independently of the activity of other processes related to seeing the image details.

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Accepted 11 May 1988