Vision Research 50 (2010) 20–30

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Effect of sampling array irregularity and window size on the discrimination of sampled gratings

David W. Evans, Yizhong Wang, Kevin M. Haggerty, Larry N. Thibos *

School of Optometry, Indiana University, Bloomington, IN 47405, United States

ARTICLE INFO

Article history:
Received 18 June 2009
Received in revised form 25 September 2009

Keywords:
Resolution acuity
Undersampling
Aliasing
Spatial vision
Conformity ratio

ABSTRACT

The effect of sampling irregularity and window size on orientation discrimination was investigated using discretely sampled gratings as stimuli. For regular sampling arrays, visual performance could be accounted for by a theoretical analysis of aliasing produced by undersampling. For irregular arrays produced by adding noise to the location of individual samples, the incidence of perceived orientation reversal declined and the spatial frequency range of flawless performance expanded well beyond the nominal Nyquist frequency. These results provide a psychophysical method to estimate the spatial density and the degree of irregularity in the neural sampling arrays that limit human visual resolution.

1. Introduction

Vision begins with the neural sampling of a continuous retinal image, a process of fundamental importance that imposes an upper limit to the spatial resolving power of the visual system. According to the sampling theory of visual resolution, when other limiting factors are avoided (e.g. filtering, noise) spatial acuity for extended gratings is set by the spatial density of neural sampling elements (Bergmann, 1858; Geisler & Hamilton, 1986; Helmholtz, 1911; Hughes, 1981; Merchant, 1965; Thibos, 1998; Williams & Coletta, 1987; Yellott, 1988). In this sampling-limited domain, resolution acuity is equal to the highest spatial frequency that can be represented veridically by the neural sampling array, the so-called Nyquist frequency. Theory predicts that retinal image components with spatial frequencies higher than the Nyquist limit may still be signaled by the array, but will be mis-perceived as “aliases” of the physical stimulus. Numerous experimental studies have confirmed this prediction in peripheral vision, where the relatively high optical bandwidth of a well-focused retinal image greatly exceeds the Nyquist frequency of the retinal mosaic (Anderson, Drasdo, & Thompson, 1995; Anderson, Evans, & Thibos, 1996; Anderson & Hess, 1990; Anderson, Mullen, & Hess, 1991; Anderson & Thibos, 1999a; Artal, Derrington, & Colombo, 1995; Coletta & Williams, 1987; Smith & Cass, 1987; Thibos, Cheney, & Walsh, 1987; Thibos, Still, & Bradley, 1996; Thibos, Walsh, & Cheney, 1987; Wang, Bradley, & Thibos, 1997a, 1997b; Williams & Coletta, 1987). Although the eye’s optical system normally serves as an effective anti-alias filter in the foveal region of the retina, thereby preventing the attainment of sampling-limited performance for central vision, aliasing has been reported when this optical limitation has been circumvented by stimulating the retina with interference fringes (Coletta & Williams, 1987; He & MacLeod, 1996; Thibos, Cheney, et al., 1987; Williams, 1985; Williams & Coletta, 1987; Williams & Collier, 1983). Within this body of work, the transition spatial frequency that separates the domain of veridical perception (supported by well-sampled retinal images) from the domain of non-veridical perception (supported by under-sampled retinal images) has been used as a non-invasive measure of the functional density of retinal neurons in the living eye.

This paper is concerned with three issues that complicate the estimation of neural sampling density from psychophysical performance when the neural sampling mosaic is irregular. First, the theoretical formulae that link the Nyquist frequency of the array to sampling density assume that density is a fixed parameter, which is strictly true only for a regular lattice. For irregular arrays, sampling density and Nyquist frequency are random variables subject to statistical variability. Taking this statistical variability into account, it might seem reasonable to suppose that visual resolution limits are set by the average sampling density of the array. However, Geller, Sieving, and Green (1992) have argued that psychophysical judgments are more likely based on isolated pockets of high sampling density, while the remainder of the array is ignored. If this be true, then psychophysical estimates would overestimate the mean sampling density, reflecting instead the maximum local density.

The second issue relates to the size of the window used to limit a grating stimulus to a finite patch. For a regular sampling array, enlarging a patch of grating to recruit more sample points does

---

* Corresponding author. Fax: +1 812 855 7045.
E-mail address: thibos@indiana.edu (L.N. Thibos).

0042-6989/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2009.10.001

not help to remove the ambiguity of aliasing caused by undersampling. Thus, stimulus size should be irrelevant for experimental measurements of the Nyquist limit of regular arrays. However, if the sampling array is irregular then expanding the stimulus would be expected to aid visual resolution because larger grating patches are more likely to include a portion of retina which happens to have, by chance, a locally elevated sampling density. Psychophysical experiments in central and peripheral vision (Anderson et al., 1996; Pokorny, 1968) have demonstrated that visual resolution of gratings increases with the number of cycles contained within a patch of sinusoidal grating. Although that result could be accounted for by spectral analysis of the stimulus, an alternative hypothesis of irregularity neural sampling could not be excluded and therefore will be reconsidered here. Such considerations are also important for reconciling sampling theory with experiments employing sampled optotypes (Carkeet, Gerasimou, Parsonson, Biffin, & Fredericksen, 2008).

The third issue is the criterion for identifying the Nyquist frequency of a sampling array, which is relevant to clinical applications such as determining functional density of neurons in diseased eyes (Chui, Thibos, Bradley, & Burns, in press). Previously we have argued that the onset of aliasing, as revealed subjectively or by the appearance of less-than-perfect performance in objective, orientation–identification tasks, is a reliable indicator of the transition from veridical to non-veridical perception and therefore is a reasonable estimate of the neural Nyquist limit (Anderson & Thibos, 1999a, 1999b; Anderson et al., 1996; Thibos, Walsh, et al., 1987). Others have preferred to estimate the Nyquist frequency as half the stimulus frequency that causes an orientation reversal phenomenon predicted by two-dimensional sampling theory in which the perceived orientation of gratings is orthogonal to the physical orientation (Coletta & Williams, 1987). Unfortunately, orientation reversals are rarely reported in studies of peripheral vision, which seems to obviate this technique for routine use. The reasons for this failure to observe orientation reversal in the peripheral field are unclear, but the possibility investigated here is that increased irregularity in the sampling array is the cause (Hirsch & Miller, 1987; Yellot, 1982).

Two experimental methods have been used previously for studying the consequences of spatial sampling on visual resolution. In the observer method, the critical sampling stage is located in the subject's retina. This is the method used by most of the studies quoted above. In the source method, the critical sampling stage is transferred to the visual stimulus by using discretely sampled visual stimuli displayed on a computer monitor and viewed foveally. (The terms "source method" and "observer method" are used here in the same way they are used in the study of optical limits to vision (Smith, Jacobs, & Chan, 1989).) In a previous study using this latter paradigm, Geller et al. (1992) found that when individual pixels in a computer display of a grating pattern were randomly deleted, performance on an orientation discrimination task did not suffer, even though the average sampling density was significantly reduced. This observation led them to conclude that psychophysical performance on a resolution task is determined by that region of the stimulus with highest local sampling density. Alexander, Xie, Derlacki, and Szlyk (1995) used a similar paradigm to study letter identification and found that random deletion of pixels on a computer monitor hampered letter identification by an amount predicted by the resulting loss of stimulus contrast. Unfortunately, the random deletion paradigm confounds the three parameters of irregularity, sampling density, and contrast. Therefore, we developed an alternative approach that allowed us to control the degree of sampling irregularity while holding constant the average sampling density and average contrast of stimuli.

Our principle aim in the present study was to evaluate current methods for estimating the density and degree of irregularity in a neural sampling array based on psychophysical measurements of performance on an orientation–identification task. A secondary aim was to delineate conditions that prevent the estimation of neural sampling density based on the method of orientation reversal. We pursed these aims with the source method that allowed systematic variation of the degree of sampling irregularity and window size on psychometric functions for the orientation discrimination task.

2. Methods

2.1. Subjects

Two of the authors (DWE and YZW) served as subjects. The stimulus was viewed foveally by the right eye from a distance of 1 m and the left eye was occluded. Refractive errors for the experimental viewing distance were corrected with spectacle lenses. The experiments were approved by the Indiana University Committee for Protection of Human Subjects and was undertaken with the understanding and written consent of each subject.

2.2. Stimulus

The stimulus was an array of dots displayed in the center of a gamma-corrected monochrome monitor (1152 (H) × 882 (V) pixels, 8 bit luminance resolution, 82 dpi, Radius, Inc.) controlled by a Macintosh computer. As illustrated schematically in Fig. 1, the dots represented sample points obtained from patches of high-contrast (80%) sine wave gratings as follows. A square patch of grating surrounded by a uniform area of the same mean luminance as the grating (40 cd/m^2) was represented in computer memory by a two-dimensional table of luminance values corresponding to the pixels of the display. For a given experimental session, the grating patch contained a fixed number of cycles ($n = 1, 2, 3, 4, 5, 6, 8, 10, 12$, or 14) and the size of the patch, which we will call the window size, was made smaller or larger from trial to trial in order to vary the grating's spatial frequency while maintaining a constant number of cycles. Anderson et al. (1996) provide a detailed account of this experimental paradigm and the advantages of co-varying window size with spatial frequency to maintain a fixed number of cycles. In the present series of experiments we modified the Anderson protocol by displaying not the grating itself, but a sampled version of the grating produced by first creating a sampling array used to extract corresponding values from the two-dimensional table of pixel luminances. Thus the output of the sampling process was a collection of grating samples the size of individual pixels on a uniform background with the same luminance as the surround. To improve the visibility of this array of samples on the computer monitor, each sample point was expanded to become a uniform, circular dot 4 pixels (1.2 mm) in diameter. The displayed dots were relatively small in comparison with their separation and were easily visible at a viewing distance of 1 m, for which the angular subtense of each dot was 4.3′. Examples of stimuli for $n = 4$ cycles are shown in Fig. 1.

As described in detail in Appendix A, the sampling array was based on a triangular lattice with center-to-center spacing S between points. For such an array the sampling density is $D = 2/(S^2\sqrt{3})$ samples per unit area and the Nyquist frequency ranges from a minimum of $1/(S\sqrt{3}) = 0.58/S$ to a maximum of $2/(3S) = 0.67/S$, depending on stimulus orientation. All sampling arrays were based on the same lattice, for which $S = 2.7$ mm (i.e. $D = 16$ samples/cm^2) on the display. Irregularity was introduced into the sampling array by displacing each point vertically and horizontally by a random amount. This spatial jitter was