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Phase noise and the classification of natural images

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Abstract

We measured the effect of global phase manipulations on a rapid animal categorization task. The Fourier spectra of our images of natural scenes were manipulated by adding zero-mean random phase noise at all spatial frequencies. The phase noise was the independent variable, uniformly and symmetrically distributed between 0° and ±180°. Subjects were remarkably resistant to phase noise. Even with ±120° phase noise subjects were still performing at 75% correct. The high resistance of the subjects' animal categorization rate to phase noise suggests that the visual system is highly robust to such random image changes. The proportion of correct answers closely followed the correlation between original and the phase noise-distorted images. Animal detection rate was higher when the same task was performed with contrast reduced versions of the same natural images, at contrasts where the contrast reduction mimicked that resulting from our phase randomization. Since the subjects' categorization rate was better in the contrast experiment, reduction of local contrast alone cannot explain the performance in the phase noise experiment. This result obtained with natural images differs from those obtained for simple sinusoidal stimuli were performance changes due to phase changes are attributed to local contrast changes only. Thus the global phase-change accompanying disruption of image structure such as edges and object boundaries at different spatial scales reduces object classification over and above the performance deficit resulting from reducing contrast. Additional color information improves the categorization performance by 2%.

Keywords: Natural scenes; Phase; Fourier; Contrast; Object categorization; Image classification

1. Introduction

Object classification and categorization is one of the most remarkable achievements of the visual system. Higher primates effortlessly classify a large number of very different and even partly occluded objects in their natural surroundings. Despite the diversity of individual natural images they share, as an ensemble, some statistical structure. It has been found, for example, that natural scenes have a characteristic 1-over-f Fourier-amplitude spectrum implying that most of the power is contained in the low spatial frequency components (Field, 1987; Thomson, 1999a, 1999b; van der Schaaf & van Hateren, 1996).

If projected into a sine-/cosine wave basis (Fourier transform), images of natural scenes thus diverge from each other primarily in terms of their phase and not their amplitude spectra. Every image can, in principle, be synthesized from sine wave gratings. For the generation of a particular image, sine gratings of the correct spatial frequency, amplitude and phase have to be combined. Phase is particularly important for edges, since edges require an alignment of the phase of different spatial frequency components. In a well-known demonstration of the importance of global phase by Piotrowski and Campbell (1982; see also Oppenheim and Lim, 1981) two images were mixed, one contributing its Fourier amplitude and the other its Fourier phase. Invariably, the resulting combination looks much more like the image contributing the phase spectrum and not like the one contributing the amplitude spectrum. Clearly, this results from the aforementioned fact that most natural images

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have similar amplitude spectra with the amplitude decreasing linearly with spatial frequency, typically termed 1-over-*f*. When the phase spectrum of an image is randomly swapped across frequencies, that is, its Fourier energy is randomly distributed over the image, the resulting image becomes impossible to recognize.

1.1. Human phase-sensitivity using simple stimuli

The importance of global phase in the Fourier representation of image structure in natural images does not imply, however, that the primate visual system necessarily encodes global phase explicitly—this would only be required if the visual system did perform a global Fourier transform of the images mapped onto its retinae, an idea that is certainly not tenable (Derrington & Henning, 1989; Henning, Hertz, & Broadbent, 1975; Westheimer, 2001). This conclusion is in line with Piotrowski and Campbell (1982) who, in addition to their demonstration of the importance of phase for image structure, also found that for recognition human observers are not critically sensitive to the precision of the encoded phase. Similar conclusions were reached by Burr (1980) and Badcock (1984a, 1984b, 1988) who examined the discrimination performance of human observers for phase-shifted gratings composed of several harmonically related gratings. Burr (1980) found phase discrimination thresholds of about 30° for all spatial frequencies tested. Badcock converted the phase discrimination thresholds of his observers to local contrast changes accompanying, willy-nilly, every phase change. Badcock concluded "the visual system does not have direct access to the spatial phase of constituent sinusoidal components in an image but instead codes the local contrast and position of image features (1988, p. 305)".

1.2. Phase-spectra of natural images and higher-order statistics

In a series of elegant articles Thomson and colleagues (Thomson, 1999a, 1999b; Thomson & Foster, 1997; Thomson, Foster, & Summers, 2000) explored the properties of phase spectra of natural images within a statistical framework. Changing the phase spectrum of an image does not affect its power spectrum (i.e., the autocorrelation function) and thus shows how little of the *content* of an image is contained therein. What phase spectrum manipulations do change, however, are higher-order image statistics (moments and cumulants of degree 3 and above). Thus edges, contours and other visually salient features cannot be captured by first- and second-order statistics but must be contained in the higher-order statistics (Franz & Schölkopf, 2005).

Thomson et al. extend the commonly used first- and second-order statistics analysis by computing higher-order image statistics attempting to find whether regularities in the phase spectra of classes of images—e.g., natural scenes—are reflected in their higher-order image statistics. Thomson (1999b) showed that (whitened) natural scenes have a strictly positive kurtosis, whereas phase-randomized versions of the very same images have positive and negative kurtosis values very close to zero.

Thomson et al. (2000) conducted a psychophysical experiment relating the structure of natural-image phase spectra to visual perception and notions from efficient coding. Note, however, that their main interest was statistical:

> "One obvious threshold psychophysical paradigm would require observers to discriminate a slightly phase-perturbed image from a natural image, but under these circumstances observers' sensitivities might be determined by one particular 'feature' in the natural images, i.e., they may not perform the tasks statistically" (Thomson et al., 2000, p. 1065).

Consistent with their statistical aims human observers in the Thomson et al. (2000) study discriminated completely phase randomized images from images with slightly less phase randomization (or quantization). None of the images looked like "natural images", i.e., subjects discriminated "cloud-like" images with power spectra derived from natural images. Subsequently Thomson et al. correlated certain higher-order statistics with their observers' performance and found phase-only kurtosis—kurtosis after removing second-order image structure—to provide a reasonable fit to their empirical data.

The aim of our study is related but different: we are precisely interested in the recognition of individual, natural "real-life" images with their multiple and possibly highly redundant features and how phase perturbation interferes with classification. We thus conducted a study akin to that outlined in the citation of Thomson et al. above: comparing image classification performance for natural images with and without various degrees of phase perturbation.

1.3. Phase-alignment across spatial scales: Edges, lines and contours

Despite the negative results of Piotrowski and Campbell as well as Burr and Badcock on finding phase-sensitive mechanisms using simple stimuli, phase-sensitive mechanisms, or whatever other mechanism such as local energy estimation (Burr, Morrone, & Spinelli, 1989; Morrone & Burr, 1988; Morrone & Owens, 1987; Morrone, Burr, & Spinelli, 1989) may detect the phase-change accompanying image changes, could be highly sensitive to particular phase relationships between harmonically related spatial frequencies. This is particularly true for detecting phase alignment at edges—the notion of alignment across spatial scales (Marr, 1982). If true, we would expect that for natural images with their complex structure of edges and object boundaries a global phase change is more disruptive than a contrast reduction—for natural images phase change could thus not simply be equated with local contrast change.

Rephrasing the above from a higher-order statistics point-of-view, it may be that phase changes in natural