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Artistic Adjustment of Image Spectral Slope

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Abstract

The Fourier spectral slope of 31 artworks was compared to the spectral slope of closely matched photographic images. The artworks were found to display a relatively narrow range of spectral slopes relative to the photographs. Two accounts for this range compression were investigated. The first proposes that the band-pass nature of the visual system's psychophysical 'window of visibility' is responsible. Simulation of this effect by application of an appropriate spatial filter to the original photographs could not explain the range compression, unless one assumed a consistent relation between the visual angle subtended by the scene at the artist's eye, and the scene's spectral slope (such that scenes with a steep slope subtended larger angles than scenes with a shallow slope). The second account involves more complex 'artistic' filtering which smoothes out textural details while preserving edges. Application of two such filters to the photographs was able to reproduce the spectral slope range compression evident in artworks. Both explanations posit a central role for the artist's visual system in adjusting image spectral slope, which can be modelled using visual filters.

Keywords

Visual art, image statistics

1. Introduction

Images of natural visual scenes display highly consistent statistical properties. A number of studies have found that the average Fourier amplitude spectrum of natural images falls off with a form $1/f^{\alpha}$ (or equivalently, $f^{-\alpha}$), where f is spatial frequency and α is approximately 1.2 (e.g. Burton and Moorhead, 1987; Field, 1987; Tolhurst *et al.*, 1992). Parameter α is commonly known as 'spectral slope'. Natural images contain most luminance contrast at coarse spatial frequencies, with contrast falling monotonically at progressively higher frequencies.

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Evidence indicates that evolution and development equip the human visual system with the ability to process natural images with high efficiency (Field, 1987; Ruderman, 1994). Each neuron acts as a filter that responds to image detail at a narrow range of spatial frequencies, with different neurons responding best at different frequencies. The range of neural sensitivities to spatial scale appears to match the spectral properties of natural images. Psychophysical studies report optimal performance in a number of visual discrimination tasks using images whose spectral slope matches the average value found in natural images (Burton and Moorhead, 1987; Hansen and Hess, 2006; Párraga *et al.*, 2000; Tadmor and Tolhurst, 1994; Tolhurst *et al.*, 1992). Subjective reports also show that visual discomfort is related to spectral statistics (Juricevic *et al.*, 2010).

Several recent papers have proposed that the visual system's tuning to natural images influences the spectral properties of visual art (Graham and Field, 2008; Graham and Redies, 2010; Redies, 2007; Redies, Hänisch *et al.*, 2007). Redies, Hänisch *et al.* (2007) reported that artistic portraits have an average spectral slope close to the most prevalent value found in images of natural scenes (namely 1.09–1.44), even though photographic portraits have much steeper spectral slopes (1.63–1.77). Fuchs *et al.* (2011) reported that the statistics of Cezanne's paintings were quite similar to those of corresponding natural images. Some degree of statistical similarity between artworks and corresponding photographic images is to be expected if the artist attempted to create a faithful representation of the scene, but the artist may make some changes during the process of rendering the scene. Mather (2014) compared scanned images of 15 closely matched pairs of paintings and photographs from a number well-known artists, and found evidence that the spectral slope values of artistic images differed slightly but consistently from those of corresponding photographs, offering support for the proposals of Graham and Field (2008) and Redies, Hänisch *et al.* (2007a).

This paper reports additional comparisons between artistic and photographic images, based on samples of work by Cezanne and Piranesi, and discusses two possible accounts to explain why the spectral slopes exhibited in artistic images might differ from photographs.

2. Material and Methods

2.1. Artistic Image Sets

Levit (1976) presented reproductions of Piranesi's eighteenth-century etchings of Rome alongside modern photographs of the same scenes. Eight of these image pairs were selected for analysis, based on the degree of preservation of the ancient scene, and the closeness of the match in viewing perspective between the artwork and photograph. Similarly, Machotka (1996) presented reproductions of Cezanne's nineteenth-century French landscape paintings alongside corresponding modern photographs. Nine of these image pairs were selected for analysis, again based on similarity in scene content and perspective. Images were scanned at 600 dpi using a Canon 8800F scanner, and down-sampled using bi-cubic interpolation so that the shorter side of each image measured 512 pixels (similar to the procedure in Mather, 2014).

2.2. *Computation of Fourier Spectral Slope*

Standard computational procedures were used to estimate spectral slope, as follows. Prior to analysis, all images were converted to grey-scale using a conventional YIQ transform. A two-dimensional discrete Fourier transform was computed on the central 512×512 pixel section of each image using built-in Matlab® functions. After each transform, a straight line was fitted to the rotationally averaged amplitude spectrum (plotted on log-log co-ordinates) and its slope calculated. In order to avoid spatial frequency artefacts due to image sampling and luminance nonlinearities, line-fitting was restricted to the middle range of frequencies lying between $0.04\times$ and $0.5\times$ the maximum spatial frequency available in the Fourier transform (see Redies, Hasenstein *et al.*, 2007; tests on random fractal images confirmed that nonlinear gamma transforms did not affect measured slope).

To validate the computation, spectral slope values were computed from a large sample of 106 photographic landscape images from the McGill image database (Olmos and Kingdom, 2004). As reported in the literature (e.g., Burton and Moorhead, 1987; Tolhurst *et al.*, 1992), spectral slope clustered around a mean value of -1.23, with very few images at the extreme values beyond -1.5 and -1.0 (see Mather, 2014).

3. Results and Discussion

In the scatter-plot shown in Fig. 1, the horizontal axis plots the spectral slope of each photograph and the vertical axis plots the spectral slope of the corresponding artwork. Open symbols plot results from Mather (2014); filled circles represent results from Cezanne's landscapes, and filled triangles represent results from Piranesi's etchings. Lines indicate best-fitting linear functions.

The spectral slopes of the photographic images in all three samples overlap substantially. The steeper slopes in Mather's (2014) sample are due to the inclusion of portrait, interior and figurative scenes. Turning to the artworks, Piranesi's etchings tend to have a shallower slope than the paintings, which overlap in terms of spectral slope. This difference is discussed later.

Despite these differences, in all three samples the range of spectral slopes exhibited by the artwork is narrower than that in the photographs. The lin-

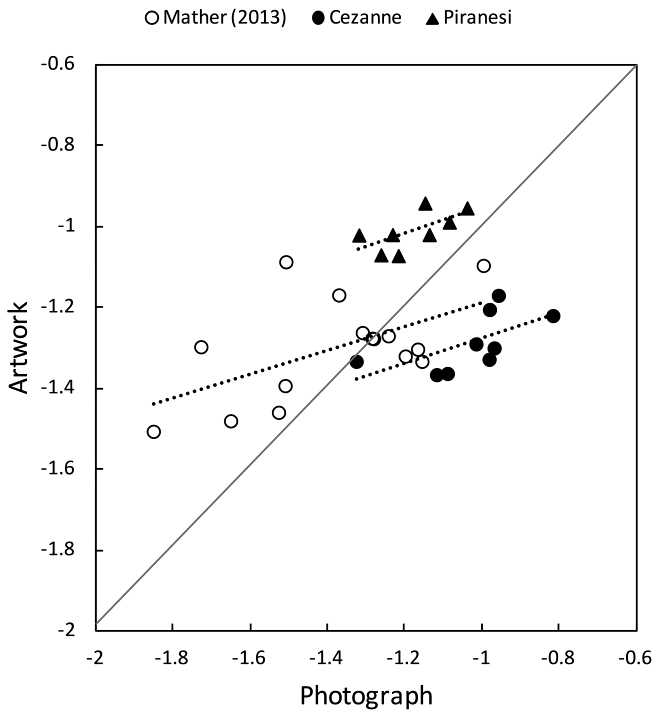

Figure 1. Spectral slope values for 31 matched pairs of artworks and photographs in three samples. Filled circles: Cezanne landscape paintings (Machotka, 1996); filled triangles: Piranesi etchings of Rome (Levit, 1976); open circles: Mather's (2014) sample of 15 artists. The grey line represents unity, and the dotted lines show best-fitting straight line functions through each data set.

ear functions are all relatively shallow, with a gradient (b) significantly below unity (Cezanne: $b = 0.31$, $t(7) = 4.52$, $p = 0.001$; Mather: $b = 0.29$, $t(13) = 5.84$, $p = 0.0001$; Piranesi: $b = 0.31$, $t(6) = 4.28$, $p = 0.003$). Two possible explanations were considered for the change in spectral slope evident in the artworks. The first relates to the concept of the psychophysical 'window of visibility'.

4. 'Visibility' Filtering

Photographic lenses act as low-pass filters that remove high spatial frequencies from the image. The human visual system, on the other hand, acts as a band-pass filter optimally tuned to medium-low spatial frequencies of about three cycles per degree (see Owsley *et al.*, 1983). Frequencies outside the passband are not visible and therefore not available for perception. The source of this band-pass filter characteristic is predominantly neural rather than optical (Webb *et al.*, 1997), and may partly reflect processing optimisations as mentioned in the Introduction. Thus, the spatial frequencies visible to an artist standing before a natural scene may differ significantly from those recorded by a camera at the same position, which may explain the change in slope evident in Fig. 1. To test the plausibility of this account, the photographic images were convolved with a spatial filter having a pass-band designed to approximate the visual system's window of visibility, and spectral slope was then calculated from the amplitude spectrum of each filtered image. Owsley *et al.* (1983) provide extensive data on the spatial frequency sensitivity of the human visual system. A two-dimensional Difference-of-Gaussians spatial filter was used to model this sensitivity: the filter's excitatory and inhibitory space constants were 0.033 and 0.198 degrees, respectively, and the balance ratio between surround and centre sensitivity was 0.9. This filter has a frequency response which closely matches human spatial frequency sensitivity (see Fig. 2) and; incidentally, is similar to that of Macaque parvo LGN cells (Derrington and Lennie, 1984).

In order to apply the filter to the photographic images, it was necessary to convert the filter's space constants from angular units to image pixels; put another way, a decision had to be made with regard to the visual angle subtended by the photographic images. It would be possible to calculate the angle of view in each photograph, given details of the camera and lens as well as any crop-

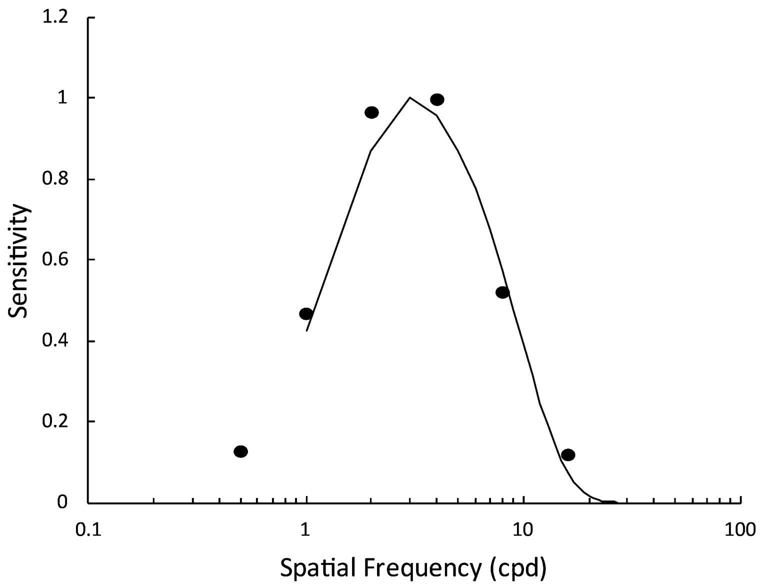

Figure 2. Filled circles: Human contrast sensitivity as a function of spatial frequency (data taken from Owsley *et al.* (1983) Table 5; for adults aged 30). Solid line: frequency response of a Difference-of-Gaussians filter with excitatory and inhibitory space constants of 0.033 and 0.198 degrees, respectively, and a balance ratio between surround and centre sensitivity of 0.9.

ping applied to the frame. Unfortunately Levit (1976), Machotka (1996) and the sources used by Mather (2014) did not supply these details. Levit's (1976) equipment included a Hasselblad (60 mm wide frame) with 59 mm, 80 mm ('standard') and 250 mm lenses; Machotka (1996) gave no details at all, but based many of his photographs on earlier source photographs taken by Loran (1963), who used a Brownie 2A with a 'standard' 105 mm lens and 82 mm wide frame. For the sake of argument, each photograph was assumed to subtend 40 arc deg horizontally (typical of a 'standard' photographic lens; after cropping each image to 512×512 pixels for Fourier analysis, image visual angle was typically 30 deg).

Figure 3 plots the spectral slope of the original photographs against spectral slope after visibility filtering. Filtering caused a significant fall in all spectral slope values. Average spectral slope in the original photographs is -1.24, while in the filtered photographs it is -0.74. But the gradient of the line relating filtered slope to original slope is 0.97, so the effect of filtering is to change all slopes by a constant amount. Further modelling showed that when

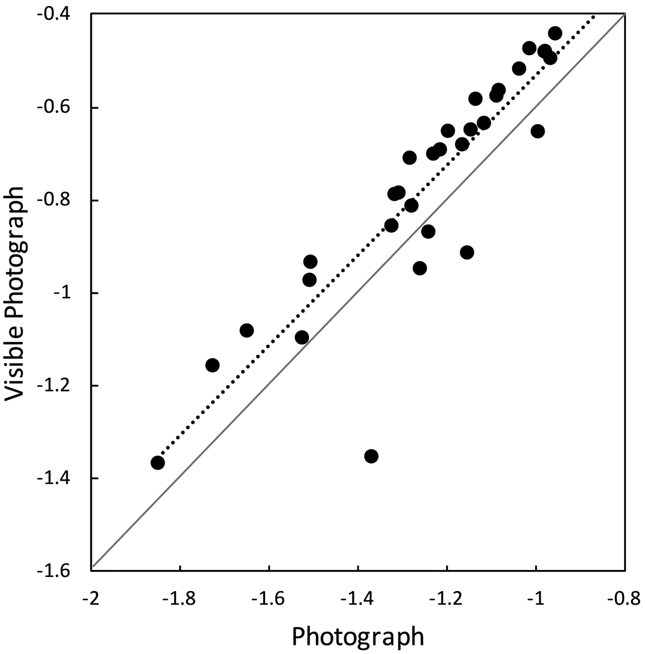

Figure 3. Spectral slope values in the sample of 31 photographs before and after filtering by the Difference-of-Gaussians filter shown in Fig. 2. The horizontal axis plots the spectral slope of each photograph before filtering, and the vertical axis plots slope after filtering. The dotted line represents the best-fitting linear function through all data points (gradient 0.97), and the grey line represents unity. Filtering assumed that each photograph subtended 40 degrees of visual angle (before cropping).

a different value is used for image subtense, the value of the constant changes. Large visual angles are associated with shallow slopes in the filtered images (due to attenuation at the low side of the filter's pass-band) while small angles are associated with steep slopes (due to high-frequency attenuation). It is possible that image subtense varied consistently across the image samples so as to produce the flattening evident in Fig. 1. The general pattern of the data of Fig. 1 is that as the spectral slope of the photographic images becomes progressively steeper, their filtered spectral slope becomes progressively shallower than it should be. This could only happen if images with steeper slopes subtended larger angles. On the basis of the regression slope in Fig. 1 it is possible to calculate the change in angular subtense that would be required to produce the relationship in Fig. 1. In the sample of Cezanne's motifs, the photograph with the shallowest original spectral slope is the view of '*La Maison du Père Lacroix*' (-0.82), while the photograph with the steepest slope is the view of '*Le Pont de Maincy*' (-1.33). According to the subtense argument, the visual angle of the latter image would have had to be 5 degrees greater than that of the former. The images with the shallowest and steepest slopes in the Piranesi motifs are '*Veduta del Ponte, e del Mausoleo, Fabbricati da Elio Adriano Imp*' (-1.04) and '*Veduta degli avanzi del Tablino della Casa Aurea di Nerone* [*second*]' (-1.32); the latter's angular subtense would have had to be 3 degrees greater to account for the data in Fig. 1. While these angular changes are quite small, it is difficult to see why there would be such a consistent relation between original spectral slope and angular subtense, as dictated by Fig. 1. This explanation requires the artists to have selected their motifs and viewing distances so that scenes which had a steep spectral slope subtended larger visual angles.

Another possible explanation for the adjustment in spectral slope seen in the artworks relates to the artistic process itself. Mark-making involves complex, highly skilled judgements by the artist concerning what and how image features should be rendered in the artwork. In recent years there has been a growth in so-called 'artistic' filtering algorithms, which aim to take a source photograph and modify it in such a way as to produce an aesthetically pleasing effect akin to an artwork. Photoshop offers a range of such filters. Given the widespread use and effectiveness of these filters, an intriguing question arises as to whether they could reproduce the change in slope evident in Fig. 1. To investigate this question, two such filters were studied.

5. 'Artistic' Filtering

Photoshop offers a 'watercolor' filter which is claimed to simplify details while preserving significant tonal changes at edges. This filter was applied to all 31 photographic images, with default parameters ('Brush Detail' 9; 'Shadow Intensity' 1; 'Texture' 1).

Papari *et al.* (2007) describe and evaluate another filter that produces 'painting-like' effects by smoothing out textural details while preserving or enhancing edges and corners. The filter defines a circular, Gaussian-weighted region around each pixel (space constant σ), divided into N sectors, over which local weighted pixel averages are computed which preserve any edges falling across the sectors; a third parameter, q, controls the degree of edge preservation. Papari *et al.* (2007) characterise parameter σ as controlling the size of the 'brush stroke'. This filter was applied to all 31 images using Papari *et al.*'s (2007) suggested parameters ($\sigma = 2$, $N = 8$, $q = 3$). Figure 4 illustrates the application of both filters to an example photograph. The effects are indeed 'painterly'. What effect do the filters have on spectral slope values, compared to the original photographs? The spectral slope of each filtered image was calculated in the usual way, and compared against the slope of the original photograph.

Open symbols in Fig. 5 show results for Photoshop's watercolour filter, and filled circles show results for Papari *et al.*'s (2007) filter. Both 'artistic' filters did indeed alter the spectral slope of the photographs in a way that is similar to that seen in the artworks. The range of slopes evident in the filtered photographs is lower than in the originals; the gradient of both lines is 0.29. It is not clear at present why the 'artistic' filters should have this effect. Both perform some smoothing or low-pass filtering on the image, but at the same time preserve (or enhance) edges.

6. General Discussion

A sample of 31 artworks was found to display a relatively narrow range of spectral slope values compared to corresponding photographic images of the same scenes. The gradient of the best-fitting line relating artwork spectral slope to photographic slope was about 0.3. One possible cause of this range compression is an adjustment of visual angle that regulates the spatial frequencies available in the image. Another possibility involves more complex filtering that produces 'artistic', painterly renderings of photographic images. Two artistic filters were also able to reproduce the spectral slope range compression evident in artworks.

Both explanations posit a role for the artist's visual system in adjusting spectral slope. In the case of visibility filtering, the artist may use viewing

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Figure 4. A source photograph (top) and 'artistic' versions of it based on Photoshop's 'watercolor' filter (middle), and Papari *et al.*'s (2007) 'artistic' filter (bottom). See text for details of filter parameters.

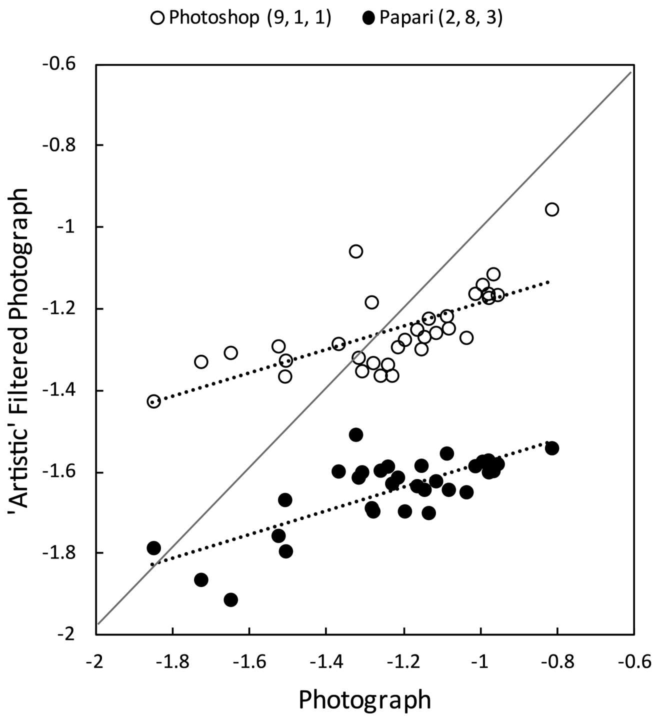

Figure 5. Spectral slope values in the sample of 31 photographs before and after 'artistic' filtering using the filters illustrated in Fig. 4. Open symbols shows results using Photoshop's 'watercolor' filter, and filled symbols show results using Papari *et al.*'s (2007) filter. The dotted lines represent the best-fitting linear functions through all data points (gradient 0.29), and the grey line represents unity.

distance as a way to control the spatial frequency content of the image, perhaps as a way to optimise the image for consumption by the human visual system (Graham and Field, 2008; Redies, Hänisch *et al.*, 2007). In the case of 'artistic filtering', a more complex rendering process which smoothes out details while preserving edges may account for the observed differences between art and photographs. The process of finding edges that define object boundaries is a crucial function of the visual system (e.g., Lee *et al.*, 1998), which may influence artistic rendering of scenes in a way approximated by artistic filters. Neither artistic filter takes account of how meaningful, and therefore worthy of preservation, are any of the edges. Nevertheless they seem to capture some basic property of both the appearance of artworks and their spectral statistics.

The artwork samples vary in terms of their mean spectral slope (Fig. 1). The mean spectral slope of Cezanne's paintings is high compared to corresponding photographic images, whereas Piranesi's etchings show a decrease in mean slope. The fine lines of Piranesi's etchings may enhance high spatial frequencies and so lower slope, whereas Cezanne's broad brush strokes may serve to smooth out high frequencies and steepen slope. Visibility filtering (Fig. 2) changes mean spectral slope in a way that depends on angular subtense. On the other hand the artistic filters (Fig. 5) either had no effect on mean slope (Photoshop) or increased mean slope (Papari *et al.*). The spectral slope evident in an artwork clearly reflects the result of a complex process involving contributions from multiple interacting factors.

An important limitation of this work is that spectral slope is but one, relatively simple, global image statistic. Paintings and photographs differ also in terms of other luminance statistics (Graham *et al.*, 2009), as well as in color statistics (Cutzu *et al.*, 2003) and changes in these other statistics may shed further light on the artistic process.

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References

Burton, G. J. and Moorhead, I. R. (1987). Color and spatial structure in natural scenes, *Appl. Opt.* **26**, 157–170.

Cutzu, F., Hammoud, R. and Leykin, A. (2003). Estimating the photorealism of images: Distinguishing paintings from photographs. *Proc. IEEE Comput. Soc. Conf. Comp. Vis. Pattern Recognit.* **2**, II-305.

Derrington, A. M. and Lennie, P. (1984). Spatial and temporal contrast sensitivities of neurones in lateral geniculate nucleus of macaque, *J. Physiol.* **357**, 219–240.

Field, D. J. (1987). Relations between the statistics of natural images and the response profiles of cortical cells, *J. Opt. Soc. Am.* **A4**, 2379–2394.

Fuchs, I., Ansorge, U., Redies, C. and Leder, H. (2011). Salience in paintings: Bottom-up influences on eye fixations, *Cognit. Comput.* **3**, 25–36.

Graham, D. J. and Field, D. J. (2008). Statistical regularities of art images and natural scenes: Spectra, sparseness and nonlinearities, *Spat. Vis.* **21**, 149–164.

Graham, D. J., Friedenberg, J. D. and Rockmore, D. N. (2009). Efficient visual system processing of spatial and luminance statistics in representational and non-representational art, *Proc. SPIE* **7240**, 72401N.

Graham, D. J. and Redies, C. (2010). Statistical regularities in art: Relations with visual coding and perception, *Vis. Res.* **50**, 1503–1509.

Hansen, B. C. and Hess, R. F. (2006). Discrimination of amplitude spectrum slope in the fovea and parafovea and the local amplitude distributions of natural scene imagery, *J. Vis.* **6**, 696–711.

Juricevic, I., Land, L., Wilkins, A. and Webster, M. A. (2010). Visual discomfort and natural image statistics, *Perception* **39**, 884–899.

Lee, T. S., Mumford, D., Romero, R. and Lamme, V. A. (1998). The role of the primary visual cortex in higher level vision, *Vis. Res.* **38**, 2429–2454.

Levit, H. (1976). *Views of Rome Then and Now*. Dover, New York, NY, USA.

Loran, E. (1963). *Cezanne's Composition: Analysis of His Form with Diagrams and Photographs of His Motifs*, 3rd edn. University of California Press, Berkeley, USA.

Machotka, P. (1996). *Cézanne: Landscape into Art*. Yale University Press, New Haven, CT, USA.

Mather, G. (2014). *Eye, Brain and Art: The Psychology of Visual Art*. Cambridge University Press, Cambridge, UK.

Olmos, A. and Kingdom, F. A. A. (2004). A biologically inspired algorithm for the recovery of shading and reflectance images, *Perception* **33**, 1463–1473.

Owsley, C., Sekuler, R. and Siemsen, D. (1983). Contrast sensitivity throughout adulthood, *Vis. Res.* **23**, 689–699.

Papari, G., Petkov, N. and Campisi, P. (2007). Artistic edge and corner enhancing smoothing, *IEEE Trans. Image Process.* **16**, 2449–2462.

Párraga, C. A., Troscianko, T. and Tolhurst, D. J. (2000). The human visual system is optimised for processing the spatial information in natural visual images, *Curr. Biol.* **10**, 35–38.

Redies, C. (2007). A universal model of esthetic perception based on the sensory coding of natural stimuli, *Spat. Vis.* **21**, 97–117.

Redies, C., Hänisch, J., Blickhan, M. and Denzler, J. (2007). Artists portray human faces with the Fourier statistics of complex natural scenes, *Network* **18**, 235–248.

Redies, C., Hasenstein, J. and Denzler, J. (2007). Fractal-like image statistics in visual art: Similarity to natural scenes, *Spat. Vis.* **21**, 137–148.

Ruderman, D. L. (1994). The statistics of natural images, *Network* **5**, 517–548.

Tadmor, Y. and Tolhurst, D. J. (1994). Discrimination of changes in the second-order statistics of natural and synthetic images, *Vis. Res.* **34**, 541–554.

Tolhurst, D. J., Tadmor, Y. and Chao, T. (1992). The amplitude spectra of natural images, *Ophthalmic Physiol. Opt.* **12**, 229–232.

Webb, R. M., Sahal, A. and Morrison, J. D. (1997). The optical quality of the human eye revisited, *Ophthalmic Physiol. Opt.* **17**, 516–521.