Factors Influencing the Sharpness of Digital Prints

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Abstract

The pixel structure associated with digital printing systems imposes image quality limitations on the print, and these may be a serious impediment to achieving the highest quality levels associated with analog prints. Print resolution or sharpness is a leading component of image overall quality, and will clearly be directly influenced by the pixel dimensions. A metric for image sharpness is proposed which combines the pixel dimensions and the perceptual response of the visual system in an appropriate Fourier-based manner. The resulting digital sharpness scale (DSS) is thus similar in approach to the digital noise scale (DNS) previously described by the author. The digital sharpness scale enables print requirements to be established for digital photography in terms of format, total number of pixels and degree of enlargement, in order to achieve the comparative sharpness levels established for conventional analog photographic processes.

Introduction

As digital printing technologies play an increasing role as the natural desk-top provider of the final print in consumer photography, it becomes of practical concern to understand both the overall level of image quality and the components which contribute to this overall quality. Conventional analog printing processes have the advantage of a long history of quality refinements, and, in order to prove competitive, digital-printing technologies must meet these established quality levels.

An important contributor to overall quality is that of image noise, in analog terms referred to variously as grain, granularity or graininess. The author has previously demonstrated1 the utility of a digital noise scale (DNS) which has a visual-perception basis yet lends itself to straightforward physical evaluation. In addition this Fourier-based scale has the advantage that it is directly related to long-established granularity metrics in analog photography, and can also be simply translated into key digital printing parameters such as dpi and number of gray-levels. The latter characteristic, ie the translation of required print sharpness into key digital photography parameters, is a matter of great concern in the progress of digital photography into the consumer market, since both sharpness and resolution are crucial criteria in determining how many camera (print-acquisition) pixels are necessary to achieve a satisfactory digital print.

This present study is concerned with the development of a comparable absolute scale for digital sharpness, with similar attributes as those of the digital noise scale. As was the case for the digital noise scale, the present digital sharpness scale (DSS) was developed without additional psychophysical experimentation or testing, but is based on a well-established descriptor for the visual transfer function associated with standard print viewing.

It should be noted that the scale does not address those many image-distorting aspects of images formed on physical grids, of which aliasing and contouring are two of the more important and obvious examples.

Detail Perception Function

Following the methodology used in developing the digital noise scale, we adopt a visual transfer function (VTF) assumed standard for normal print viewing conditions,[2] as shown in figure 1.

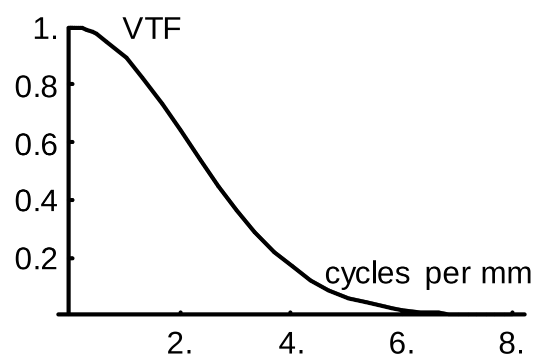

Figure 1. The assumed visual transfer function for standard print viewing condition

We must now consider the introduction a spatial-frequency spectrum that will act as a global surrogate for those aspects of the input (scene) which convey the impression of sharpness. For this we assume a spectrum which increases linearly with spatial frequency, and the resulting product of this spectrum and the visual transfer function is shown in Figure 2.

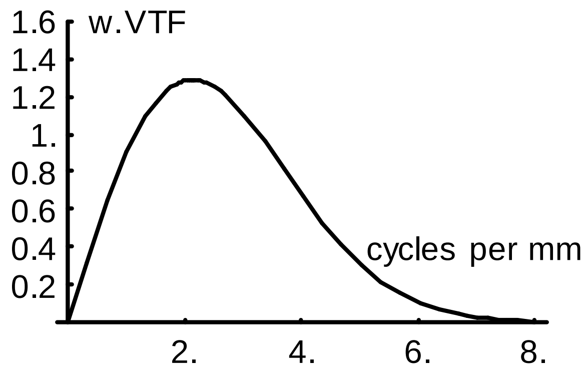

Figure 2. The visual spatial-detail detection-function

The product shown in Figure 2 may be thought of as a spatial-frequency detection-function, and in this sense is similar in form to many results found in the literature pertaining to the visual detection of sine-waves, and variously referred to as sine-wave detection functions, visibility curves, etc. The nature of these curves, and specifically the decreasing response at very low spatial frequency response, arises from the fact that the number of cycles available for detection within a fixed viewing angle is a linear function of spatial frequency. A recent extensive report on these and other aspects of visual response and the visual transfer function is given in reference 3. From the viewpoint of Fourier mathematics the frequency-weighting of figure 2 arises simply from the radial integration of the point-symmetric frequency spectrum.

Transfer Function for Pixel Array

For the present purposes the transfer function associated with the digital printing process is considered to be due entirely to the pixel grid structure and can therefore be represented by a *sinc* function based on the pixel dimensions in the standard. Figure 3 shows this function for pixel sizes of 4, 8, 16, 32, 64, 128 and 256 microns.

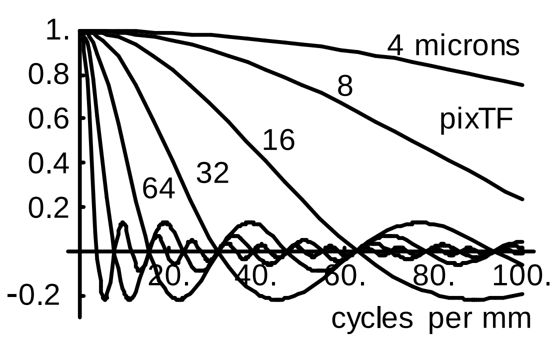

Figure 3. The pixel-grid transfer-function for various pixel sizes.

We note that any additional factors influencing the overall transfer function in the overall chain from scene-acquisition to printing (most obviously transfer functions of optical components such as camera lenses) may be introduced as appropriate. The intention here is to derive a metric for print sharpness that describes the fundamental limitation due to the grid structure of the image.

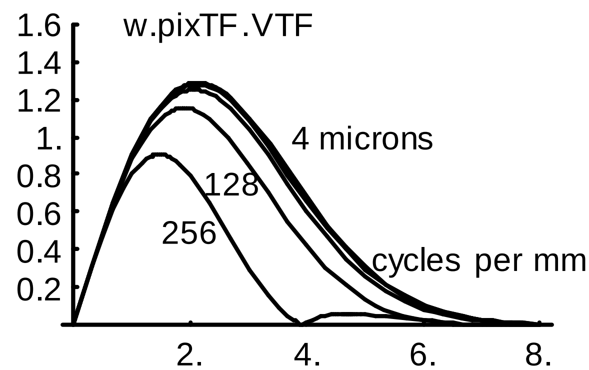

Figure 4. The overall spatial-detail detection-function

The transfer function for the pixel array is now combined with that of figure 2 to yield an overall spectrum for spatial-detail detection function, again for a range of print pixel-dimensions. Since the smaller pixel-sizes have spatial frequency band-passes far beyond that of the visual system, the curves shown in figure 4 crowd together for these small pixel sizes, the limiting curve of course being simply that of figure 2.

The Digital Sharpness Scale

We now hypothesize the spatial-frequency integral of the above curves as a metric of perceived print sharpness, or the digital sharpness scale (DSS). This integral is shown in figure 5 as a function of print pixel size.

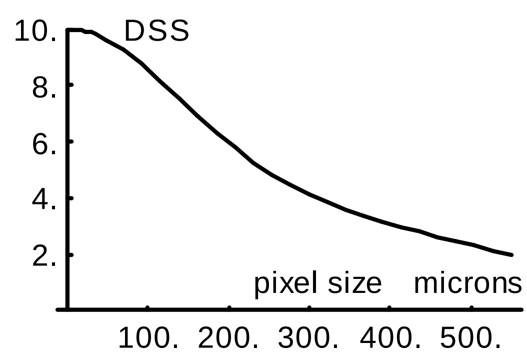

Figure 5. The digital sharpness scale (DSS) as a function of print pixel size.

For convenience the scale has been normalized to 10 for an arbitrarily small pixel (ie, the integral of the function shown in figure 2), yielding a convenient 0 to 10 scale for the complete gamut of sharpness values. It should be stressed here that the pixel size refers to that effective in the viewed print, and in digital photography this may be greater than the basic print-resolution dimension - and is always almost greater than the pixel dimension associated with image acquisition in the camera. We will consider these factors shortly. First however we reinterpret the relationship of figure 5 into more familiar digital-printing terms by conversion to *pixels-per-inch* (ppi), and the result is shown below in figure 6.

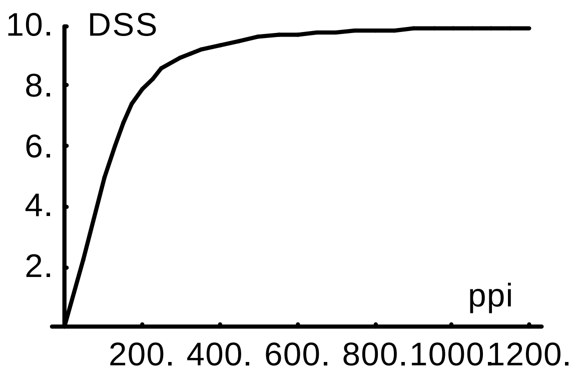

Figure 6. Digital sharpness scale (DSS) as a function of print ppi.

We note from figure 6 that according to the digital sharpness scale there is an almost linear increase in sharpness up to around 150 ppi. Thereafter further increases in ppi bring diminishing sharpness benefits, while beyond 600 ppi print sharpness approaches its upper limit in asymptotic manner. Of course these two values of ppi both have practical significance in the recent rapid evolution of desk-top printers, and we see that from a sharpness viewpoint this is no mere coincidence.

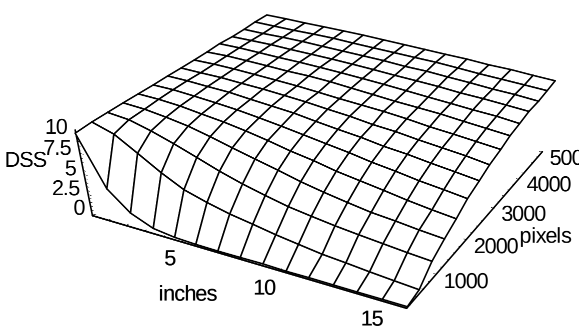

Figure 7. Digital sharpness scale (DSS) as a function of print size and number of camera pixels in this dimension.

Sharpness in Digital Photography

In digital photography, while the print is the final stage of the imaging chain, the effective pixel size in the print will be determined by the camera pixel-size in effect during the image-acquisition stage. We assume here that the latter size, with appropriate adjustment for the degree of enlargement between camera format and print, defines the print pixel-size, and note that this may be less than the basic printer capability, or *dpi*. Thus for digital photography ppi- as implicit in the digital sharpness scale- may be defined simply in terms of the dimensions of the print (say the x-dimension) and the number of camera-sensor pixels in this same dimension.

Figure 7 shows a three-dimensional representation of this sharpness relationship, which serves as a convenient way of expressing the maximum print size which is permissible for a given sensor array, under a specified sharpness requirement. A simplified version is shown in figure 8, where the sharpness associated with a series of practical print dimensions is shown as a function of the number of sensor pixels.

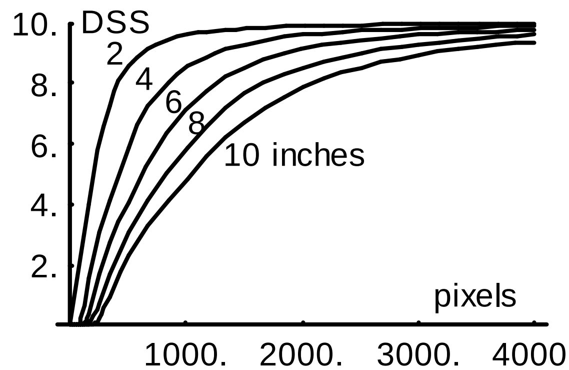

Figure 8. Digital sharpness scale versus sensor x- pixels for a series of print x-sizes.

As with the digital noise scale, once established the important question arises of reasonable requirements for print sharpness, and this of course will depend on expectations for the application at hand. Such expectations for digital photography are relatively easy to quantify, at least to a first-order approximation, due to long-established experience in analog photography.

Sharpness in Analog Photography

For the present purposes we illustrate the range of sharpness values associated with consumer analog photography by simplistic but illustrative assumptions concerning the origins of analog sharpness. First the equivalent pixel-size in the negative is assumed to fall within the practical range of 5 to 10 microns - practical values estimated from the spread function diameters of typical modern negative materials. Secondly, the practical format/enlargement range of interest is assumed to fall between the extremes of APS format enlarged to 8" inch prints and 35mm format to 3.5" prints. Combining all these assumptions leads to an estimation for the practical range of spread-functions as falling between 20 and 120 microns in the analog print, with corresponding sharpness values varying between 8 and 9.95 according to the digital sharpness scale. In this sense the scale parallels that of the digital noise scale, in so far as practical high-quality photography falls somewhere within the last two units of the 0 to 10 scales (the bottom two in the case of digital noise where of course more noise signifies less quality).

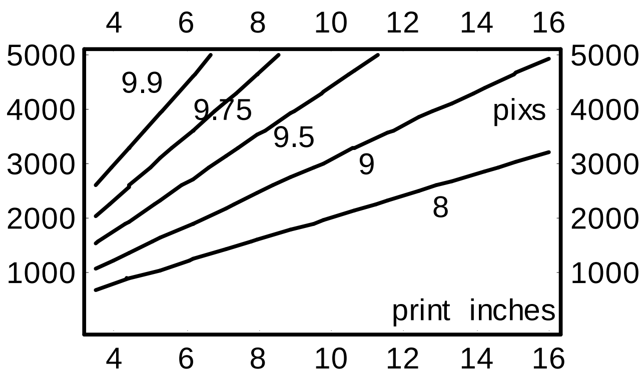

Figure 9. Relationship between number of sensor x-pixels and print x-dimension in order to conform to the range of sharpness values typical for analog photography.

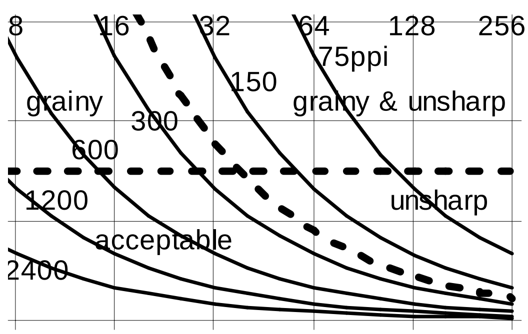

Figure 10 . Gray levels (vertical, scale at top) and ppi (contours as shown), and regions bounded by dashed curves for sharpness (DSS=8.5) and noise (DNS=1.5).

Figure 9 shows constant-sharpness contours for sharpness values within this practical photographic range - as argued above - in terms of print size and number of camera sensor-pixels. This demonstrates, for example, that achieving a sharpness value as high as 9.75 associated with an 8" digital print implies a camera sensor having 5000 pixels in this same dimension! We recall that the present model for digital photography does not include other sharpness-modifying components such as camera lenses and apertures, but that such factors can readily be included in the spatial frequency integration as appropriate - inevitably leading to lower sharpness levels than those shown above.

Quality Boundaries in Digital Photography

Finally we consider the mutual implications for both digital noise and digital sharpness capabilities according to these new scales, since both have now been related back to the basic printing-technology parameters of ppi and number of available gray levels.

Figure 10 shows a representation of such quality boundaries in terms of the basic determinants of sharpness and noise imposed by the available number of gray levels and the ppi capabilities associated with the printing technology. For this example it has been assumed that an acceptable level of noise is defined by DNS = 1.5 or less, and likewise that an acceptable level of sharpness is defined by DSS = 8.5 or greater. With digital noise shown as the vertical scale and number of gray levels as the horizontal, these respective noise and sharpness criteria lead to the establishment of four quality regions as defined by the intersection of the criteria-curves. These are namely a region with unsatisfactory sharpness, one with unsatisfactory noise, one with unsatisfactory sharpness and noise, and one that is satisfactory on both counts.

It is interesting to note that according to the reasonable practical assumptions made for sharpness and noise this specific intersection is located at around 250 ppi with between 32 and 64 gray levels. Separate practical experience indicates that the achievement of these printer capabilities delineates between general desk-top printing and the printing of high-quality digital photographs.

Summary and Conclusions

A visual Fourier-based model has been developed to account for the perceived sharpness of digital prints, and an absolute scale has been proposed to allow inter-comparison between different technologies (eg, analog and digital photography). The basic influence of the print pixel size had been demonstrated, allowing the effect of camera format, number of pixels and degree of enlargement to be quantified according to the digital sharpness scale. The scale has also allow practical quality regions for sharpness and noise to be simultaneously defined in terms of their basic properties of ppi and available gray-levels.

References

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Biography

Rodney Shaw received his PhD from Cambridge University. He came to the USA in 1973, and following research appointments at Xerox and Eastman Kodak was Director of the Center for Imaging Science at RIT. He joined H-P Labs in 1994, and his current interests are in digital photography and systems modeling.

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