Image enhancement for the visually impaired

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Abstract. Application of image processing for the visually impaired is discussed. Image degradation in the low vision patient's visual system can be specified as a transfer function obtained by measurements of contrast sensitivity. The effectiveness of adaptive image enhancement for printed pictures is demonstrated using an optically simulated cataractous lens.

Keywords: image processing; adaptive image enhancement; contrast sensitivity; low vision; visual impairments.

Optical Engineering 23(1), 047-051 (January/February 1984).

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1. INTRODUCTION

The exact number of persons with visual impairments is unknown, varying with the definition of visual impairment. Recent estimations put the number of severely visually impaired people who cannot read a newspaper at 1.5 million.[1] Additionally, there are about 10 million people in the United States who cannot read small print or material that is printed in certain colors or on certain types of paper. This large population justifies the need for printing and publishing guidelines.

There are a number of special large print publications that follow most of the guidelines for printing text for low vision patients. However, pictures are generally presented with no special processing. Some publications restrict themselves to illustrations in the format of line drawings only. Others avoid the problem by not displaying pictures at all. A few publications do try to enhance the pictures for their readers. The *Reader's Digest* large type edition attempts to enhance contrast by using black-and-white reproductions, enlarged by 50%, of the colored pictures printed in its regular edition. In addition, edge enhancement, achieved by cutting out pictures along main contours and printing the cut versions on white backgrounds, is obtained. If a picture is too detailed or has insufficient contrast, it is omitted from the special large print edition. The techniques used indicate the need for better image enhancement capabilities in the large print publications. Similar processing can be applied to ordinary newspapers and magazines, increasing the choice of material available to the visually impaired.

One way to compensate for image degradation in a low vision condition is to apply the inverse of the spatial transfer characteristics of the low vision system to the image. However, this direct approach does not produce satisfactory images. Instead, we apply another technique, adaptive image enhancement,[2] which is generally superior and allows good control of the final result. We will demonstrate the effect of adaptive image enhancement using an optically simulated cataractous lens.

In this report we are concerned only with the enhancement of black-and-white pictures. The use of colored pictures is advantageous because the additional information contained through color contrast might be helpful to a low vision observer. However, today's high quality color printing techniques use highly glossy paper and specularly reflective printing ink. This results in significant reflected glare from the page and, therefore, is not recommended for use in low vision publications.[3]

2. VISUAL DEGRADATION TRANSFER FUNCTION

In order to compensate for visual degradation, we first have to know the characteristics of such image degradation of the low vision patient. Spatial filtering characteristics of the visual system are studied by measuring visual sensitivity to sine wave grating patterns.[4] The gratings are composed of sequential space-varying sinusoidal bars. Two parameters of the grating are varied—the contrast of the pattern and its frequency. The contrast threshold required for detection for a range of frequencies specifies the spatial filtering characteristics of the visual system. Its reciprocal is defined as sensitivity, and when plotted as a function of spatial frequency, it is called a contrast sensitivity function (CSF). This function specifies the spatial filtering characteristics of the visual system at threshold. If one assumes, as a first approximation, that the visual system is linear,[5] homogeneous, and isotropic,[6] the CSF can be utilized as a modulation transfer

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Paper 1937 received Feb. 25, 1983; revised manuscript received May 27, 1983; accepted for publication June 16, 1983; received by Managing Editor July 20, 1983. This paper is based on an oral presentation given by the authors at the Annual Meeting of the American Academy of Optometry, Dec. 14, 1982, Philadelphia, Pennsylvania.

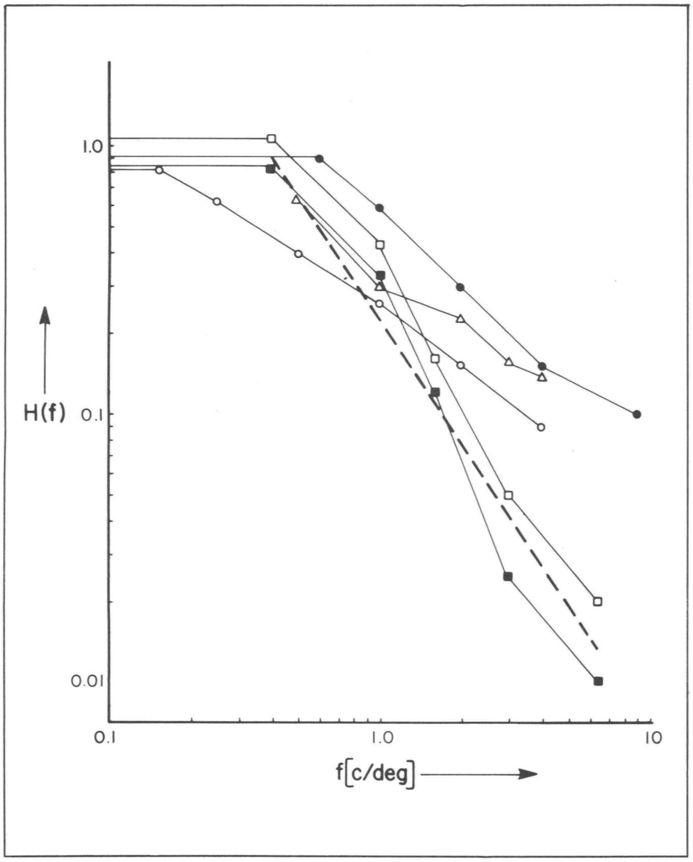

Fig. 1. The visual degradation transfer function (VDTF)—the ratio of the CSF from a diseased eye to the CSF obtained from a normal healthy eye. Shaded squares: VDTF for cataracts averaged from ten patients' CSFs presented by Brown.[8] Open squares: senile macular degeneration averaged VDTF from seven patients.[8] Open circles: keratoconus averaged VDTF from six eyes.[9] Shaded circles: corneal dystrophy.[9] Triangles: Devie's disease—one patient.[10] Broken line: a representative VDTF used in the simulations.

Fig. 2. Enhancement by high-pass filtering. The filter used is the inverse of the representative VDTF marked with a broken line in Fig. 1. Note the "salt and pepper" appearance of the image. The original image is presented in Fig. 4(a).

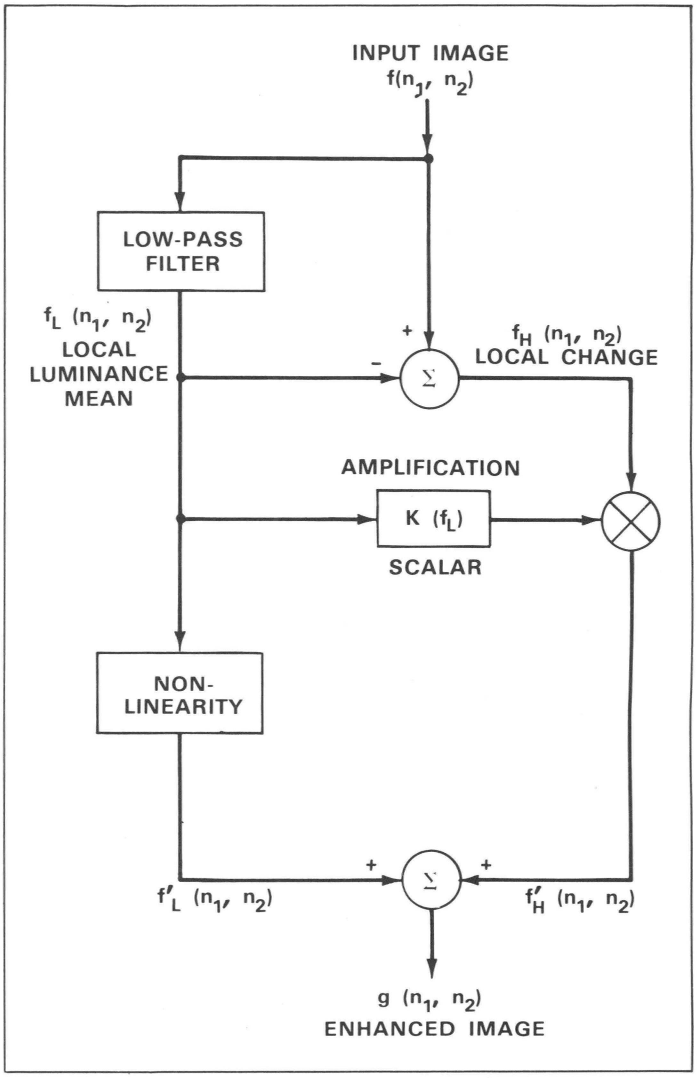

Fig. 3. Block diagram of the adaptive enhancement algorithm.

function (MTF). In turn, the MTF is used to determine the visual system response to any arbitrary stimuli by application of Fourier analysis.

Visual system characteristics are affected by a variety of diseases and aging processes, each affecting different aspects of the visual mechanism and resulting in a different nature of impairment. Some conditions involve opacification of the optical media, resulting in significant intraocular light scatter. Others affect the light detecting neurons of the retina or the neurons carrying the signal from the eye to the brain. CSFs of low vision patients were reported for conditions such as cataracts,[7,8] macular degenerations,[8] corneal dystrophies,[9] demyelinating diseases,[10,11] amblyopia,[4] and congenital coloboma.[4] The CSF of an eye with abnormal vision is useful only when compared to a CSF of an eye with normal vision. Yet there is no single accepted way of comparing the two. One typical method of comparison is to plot a normal CSF and a CSF obtained from a diseased eye on one graph. Another, the visuogram,[4] presents the difference in decibels between a normal eye and a diseased eye. A third, the contrast ratio,[7] is the ratio of the CSF response of a cataractous eye to the response of a normal eye, indicating the attenuation of contrast due to cataracts. In most conditions, the loss of contrast sensitivity is spatial frequency dependent, representing the spatial filtering characteristics of the low vision condition. Therefore, we chose to use this ratio and refer to it as the visual degradation transfer function (VDTF). We calculated the VDTF from a number of previous reports. As can be seen in Fig. 1, the VDTFs of various conditions

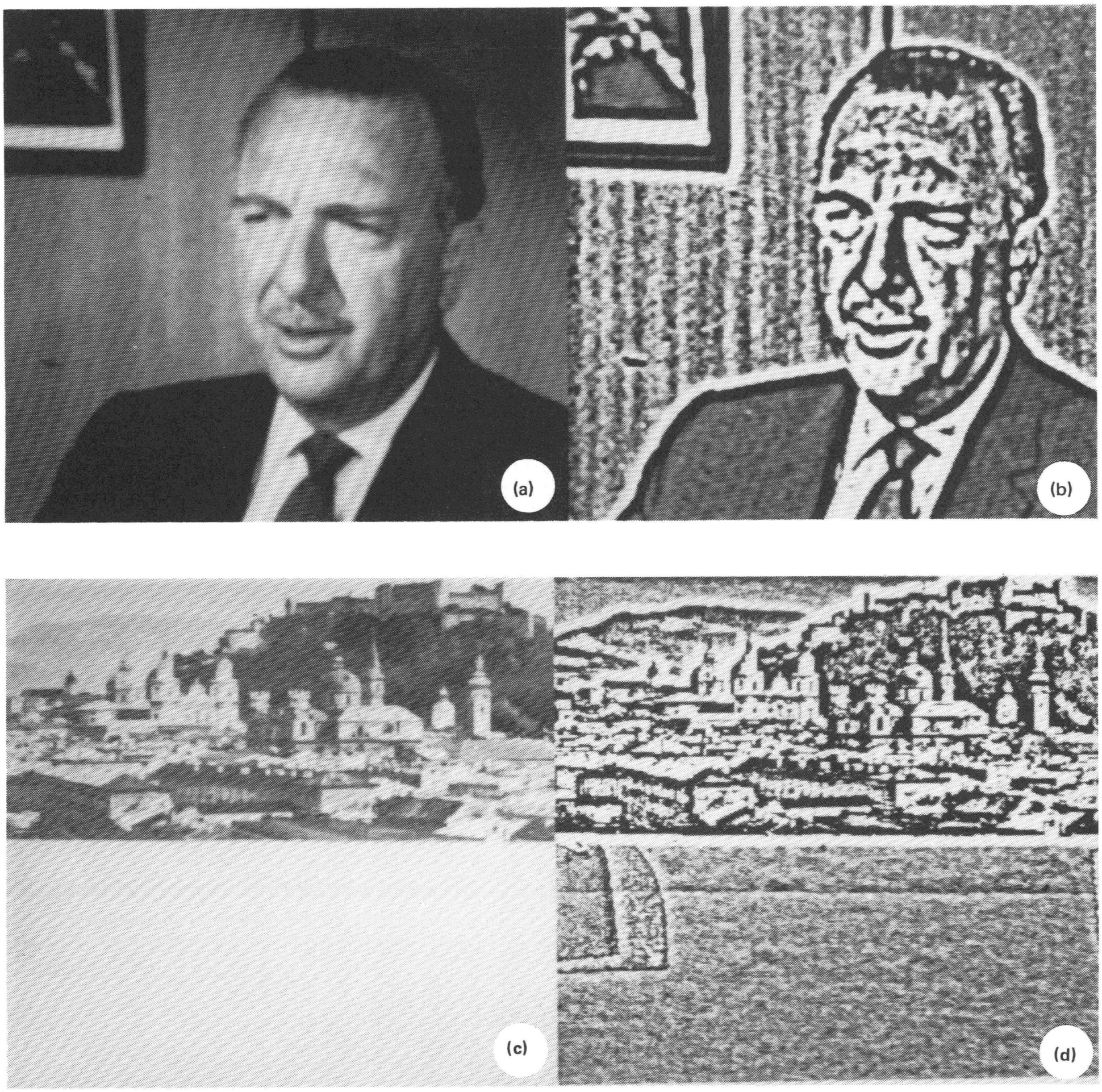

Fig. 4. The adaptive image enhancement algorithm applied to two images of different spatial frequencies content. (a) Original image. (b) Enhanced image. (c) Original image. (d) Enhanced image.

behave similarly, despite the differences in the nature of the impairments. We estimated a representative transfer function that approximates the VDTF of cataracts and senile macular degenerations—the most common impairing conditions.

The direct approach to compensation for image degradation is a preemphasis filtering.[12] If we know the effect of the degradation, as we do in the case of our low vision patient, we can compensate for this by applying an inverse filter to the image before it is entered into the visual system. The representative VDTF (Fig. 1) is a low-pass filter, and therefore its inverse is a high-pass filter. Unfortunately, high-pass filters have a number of disadvantages. They tend to enhance the noise and the signal at the same time.[13] Digital image processing introduces an additional limitation to the application of high-pass filtering. Only a limited range of gray level values is used to represent luminance on a display. High-pass filtering might result in many points with out-of-range values that require clipping. If a clipping is performed, the filtered (enhanced) image has a noisy appearance of the "salt and pepper" type (Fig. 2). Such a picture is very unattractive to an observer with normal vision. Subsequent low-pass filtering of the noisy image will reduce some of the noise,[14] but the clipping effect is irreversible, i.e., there is a net loss of information. As we see in Fig. 2, the image processed by direct

Fig. 5. The original and the enhanced images presented in Fig. 4 as seen through a simulated cataract.

inverse filtering is not satisfying. Instead, we chose to apply an adaptive image enhancement technique that can overcome some of the disadvantages of the direct approach.

3. ADAPTIVE IMAGE ENHANCEMENT

Originally, an algorithm was developed for images degraded by cloud cover and/or shadows.[2] The adaptive nature of the algorithm results from the fact that the image is processed a pixel at a time based on its local characteristics. A block diagram of the algorithm is given in Fig. 3. The algorithm separates the image into two basic components: the local luminance mean (low frequencies content of the image) f_L and the local high frequencies content f_H, which is analogous to local contrast. We assume that these two components are affected by the degrading media, such as cataracts, and in order to enhance an image we should process these two components. The algorithm amplifies the local high frequencies component and shifts the local luminance level towards the midrange, both as a function of the local luminance mean.

The local luminance mean $f_L(n_1,n_2)$ is obtained by a weighted local averaging of the original image $f(n_1,n_2)$ using a mask size of $(2N_1+1)\times(2N_2+1)$ and is given by

$$f_L(n_1,n_2) = \frac{1}{U} \sum_{k=n_1-N_1}^{n_1+N_1} \sum_{j=n_2-N_2}^{n_2+N_2} f(k,j)\,W(k-n_1,j-n_2) \ , \tag{1}$$

where W is a Gaussian shaped window with controllable variance, and

$$U = \sum_{k=-N_1}^{N_1} \sum_{j=-N_2}^{N_2} W(k,j) \; . \qquad (2)$$

The local high frequencies content $f_H(n_1,n_2)$ is obtained by subtracting $f_L(n_1,n_2)$ from the original image $f(n_1,n_2)$. It is then amplified by multiplying $f_H(n_1,n_2)$ by $K[f_L(n_1,n_2)] > 1$, a scalar which is a function of the local luminance mean. The local luminance mean is modified by a point nonlinearity that shifts the local mean towards the midrange. This is given by

$$f_L'(n_1,n_2) = [f_L(n_1,n_2) - 128]\,L(f_L) + 128 \;, \qquad (3)$$

where 128 is the value of the midrange, and L is a scalar which is a function of the local luminance mean and whose range is set by $0 \leq L \leq 1$.

The two processed components $f_L'(n_1,n_2)$ and $f_H'(n_1,n_2)$ are added together to produce the final processed image $g(n_1,n_2)$.

The ability to control the local luminance mean is advantageous in two ways: By reducing the luminance mean where it is very high and by increasing it where it is very low, we can avoid the clipping effect that otherwise would result from amplifying the high frequencies content in such areas. This results in a significant reduction of the "salt and pepper noise" effect. At the same time, the contrast is increased by reducing the local luminance mean (the contrast is defined as $\Delta I/I$, i.e., the change in luminance over background luminance). By reducing I (which is the local luminance mean), we can achieve better detectability of contours than is possible by only increasing ΔI. The adaptive feature of the algorithm enables us to affect different areas of the picture in different ways. Since the operation can be interactive, one can change the parameters controlling $K(f_L)$ and $L(f_L)$ until a desirable effect that might be considered more informative is obtained at some part of the picture.

The performance of the algorithm is demonstrated on two pictures: one with most of the energy at the low frequencies range [Figs. 4(a) and 4(b)] and the other with significantly more energy than the first in the high frequencies range [Figs. 4(c) and 4(d)].

To test the effectivity of the enhancement we chose to use photographic simulation of vision through cataracts. Zuckerman et al.[15] have shown that a cataract can be modeled as an optical element containing a random distribution of scattering centers. The scattering centers introduce random-phase abberations on the optical wavefront. Using measurements with both laser illumination techniques and incoherent illumination, it was shown that cataracts can be simulated quite accurately with a camera lens of appropriate f number covered with a random-phase medium, such as can be obtained with a thin layer of petroleum jelly. Using this method, we took pictures of projected slides of the original image and the enhanced one. We used an f/5 lens, and 50% of the lens was covered with the petroleum jelly. As can be seen from the results (Fig. 5), the degradation of the simulated cataract is more effective on the picture of the old city than on the face. Note that while the old city has significant high frequency content, the face is predominantly low frequency. Note also that enhancement improves both pictures, enabling better determination of details and even permitting recognition of the face of the person.

4. CONCLUSIONS

Adaptive image enhancement was shown to provide an effective means for compensating the visual degradation of images that result from simulated cataracts. Experiments with patients with cataracts should be conducted to support these results. The need for compensatory image enhancement is growing due to an increasing number of older people with degenerative eye diseases. A similar enhancement of images can be applied to regular newspaper pictures. Such enhancement can compensate for the poor dynamic range of pictures in newsprint and can help the reader with reduced sensitivity in the spatial high frequency range. Such deficit in sensitivity is common even for healthy people over the age of 60 with no eye disease.[16] Older people were shown to have significant difficulty in detecting and recognizing face pictures[16] and other low contrast images commonly encountered in newspapers. Enhancement of images printed in the papers is of great potential value to members of this growing part of the population. A real-time hardware device capable of performing a similar adaptive contrast enhancement of video pictures is available.[17] Such a device can serve to enhance TV images for the low vision population.

5. ACKNOWLEDGMENT

This work was supported in part by the U.S. Air Force. The U.S. Government assumes no responsibility for the information presented.

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