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Rapid and brief communication

Proposing new methods in low-level vision from the Mach band illusion in retrospect

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Abstract

A re-scan of the well-known Mach band illusion has led to the proposal of a Bi-Laplacian of Gaussian operation in early vision. Based on this postulate, the human visual system at low level has been modeled from two approaches that give rise to two new tools. On one hand, it leads to the construction of a new image sharpening kernel, and on the other, to the explanation of more complex brightness-contrast illusions and the possible development of a new algorithm for robust visual capturing and display systems.

Keywords: Early vision; Edge enhancement; Laplacian; Brightness-contrast illusions; Disinhibition

1. Introduction

It was postulated by Marr and Hildreth [1] that the response function for the receptive fields (RF) of the ganglion cells in the retina or the cells in lateral geniculate nucleus (LGN) may be represented by a Laplacian of Gaussian (LOG) that filters the two-dimensional intensity array falling on the retina. The information thus extracted is then sent to the visual cortex in the brain, where an edge-map, representing a "raw primal sketch" of the external world, is formed. It was further demonstrated by Marr and Hildreth [1] that the LOG operator in fact approximates the lateral inhibition-based difference of Gaussian (DOG) model of the RF of these cells as proposed by physiologists. Interestingly, these two interrelated phenomena, namely lateral inhibition in physiology and Laplacian operation in computation, were predicted almost a century ago, by the eminent physicist Ernst Mach [2]. He did so from his observation of a particular visual illusion, now popularly termed theMach band illusion, shown in Fig. 1a. By scanning this image in a direction in our which the luminance increases or decreases, ourvisual system perceives an actually non-existent darker bar at the location where the figure just starts getting lighter. Similarly, a brighter bar is perceived at the point where the brightness just stops increasing. This observation led Mach to foresee the mechanism of lateral inhibition in the retina and propose a mathematical model for visual signal processing based on a linear combination of the original intensity function and its second differential coefficient [2]. One can easily make a finite difference approximation of the operator $\partial^2/\partial x^2 + \partial^2/\partial y^2$, to arrive at an orientation-independent filter mask L [3], L signifying Laplacian. The horizontal line profile of Fig. 1a convoluted with this mask has been shown in Fig. 1b. Instead of adding this convoluted image to the original, for enhancement one can also filter the original image with the mask L' [3]. The horizontal line profile of the resultant image is shown Fig. 1c, where a simulation of the illusive perception is produced in the form of undershoots and overshoots at each step transition, in contrast to the simple staircase-shaped horizontal scan of the original image in Fig. 1d. The mask L' has the ability to enhance any image by sharpening its edges as may be seen in Fig. 2b. L and L' have been shown below, along with a new mask M,

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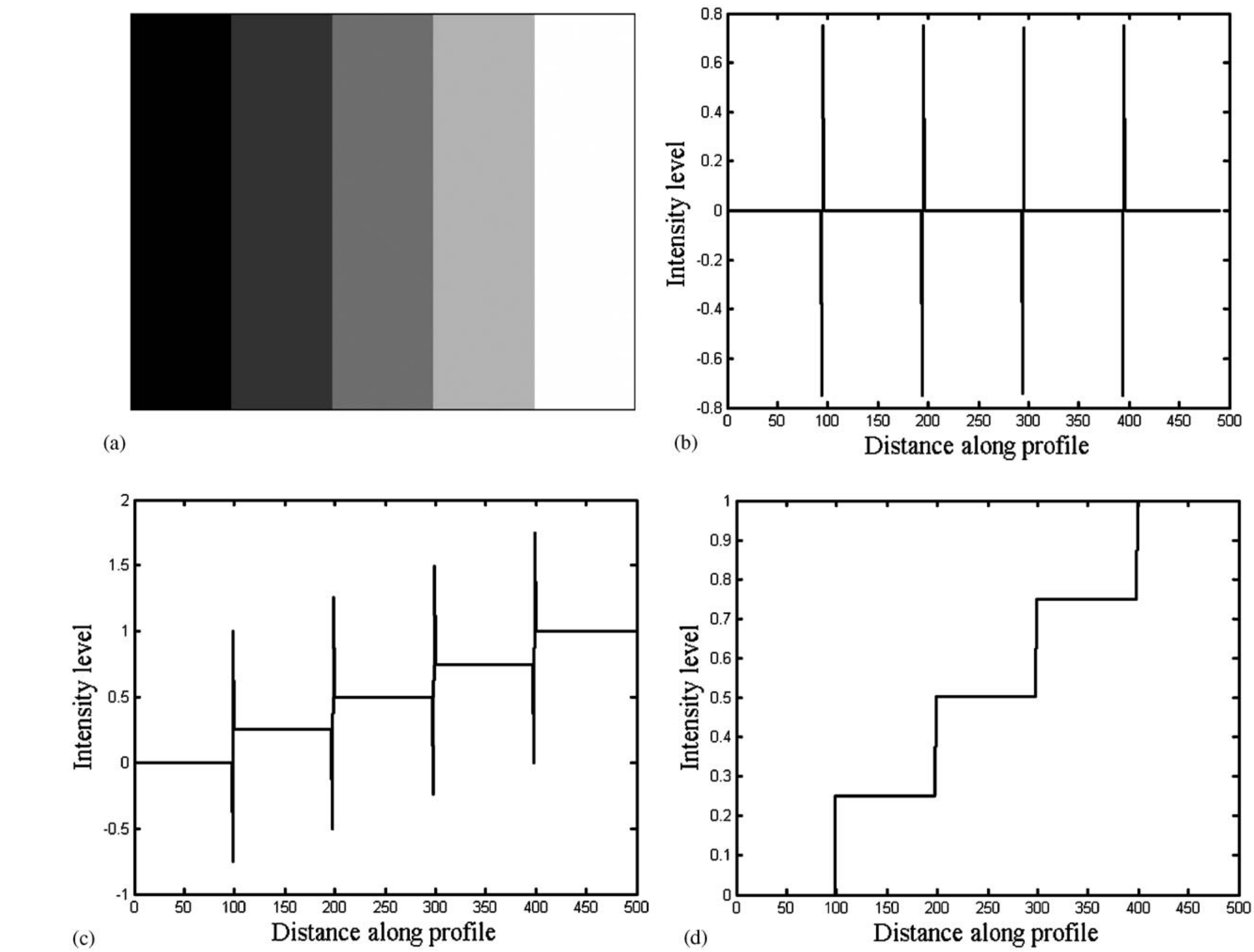

Fig. 1. (a) The Mach band illusion of dark and bright borders around bright and dark regions respectively, (b) the horizontal profile of image (a) convoluted by L, (c) the horizontal profile of the image (a) convoluted by L'; and (d) horizontal profile of the original image (a).

derivation of which has been discussed in the next section.

$$L = \begin{pmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{pmatrix} \quad L' = \begin{pmatrix} -1 & -1 & -1 \\ -1 & 9 & -1 \\ -1 & -1 & -1 \end{pmatrix}$$

$$M = \begin{pmatrix} -1 & -1 & -1 & -1 & -1 \\ -1 & 3 & 3 & 3 & -1 \\ -1 & 3 & -7 & 3 & -1 \\ -1 & 3 & 3 & 3 & -1 \\ -1 & -1 & -1 & -1 & -1 \end{pmatrix}.$$

2. Proposed method

Before, proposing any new method, let us first explain the reason behind the edge enhancement in Fig. 2b. The light Mach bands around dark regions and the dark ones around lighter, apart from being illusions, play a crucial role here. They actually represent a mechanism of contrast sensitivity in the eye that enables one to clearly isolate an object from its background, thus helping in image enhancement. The sharpening operator L', based on this principle of excitatory–inhibitory mechanism following Mach's idea, which is also apparent from the polarities in the digital mask, is also orientation independent [3]. It therefore naturally forms these Mach bands in all directions in an image, thus enhancing the images from objects of any arbitrary shape.

But if, on the other hand, we try to explain the Mach band illusion (Fig. 1a) in terms of the "raw primal sketch" model of Marr and Hildreth [1], we realize that the same phenomenon requires a detection of three and not one edge point, at each of the gray level transitions, where one of these three edges, the central and the major one should represent the real transition in gray level, while the two minor edges should represent the illusory transitions in gray level on either side of the real edge. This is only possible if the convolution filter is $\nabla^4 G$ and not Marr's $\nabla^2 G$ operator. This has been shown for a one-dimensional step edge in Fig. 3. The $\partial^2 G/\partial x^2$ operator produces only one zero-crossing (i.e. one edge) at the step transition, but the $\partial^4 G/\partial x^4$ operator produces one major zero-crossing and two minor ones on either side of it, or in other words three edges, one "strong" and