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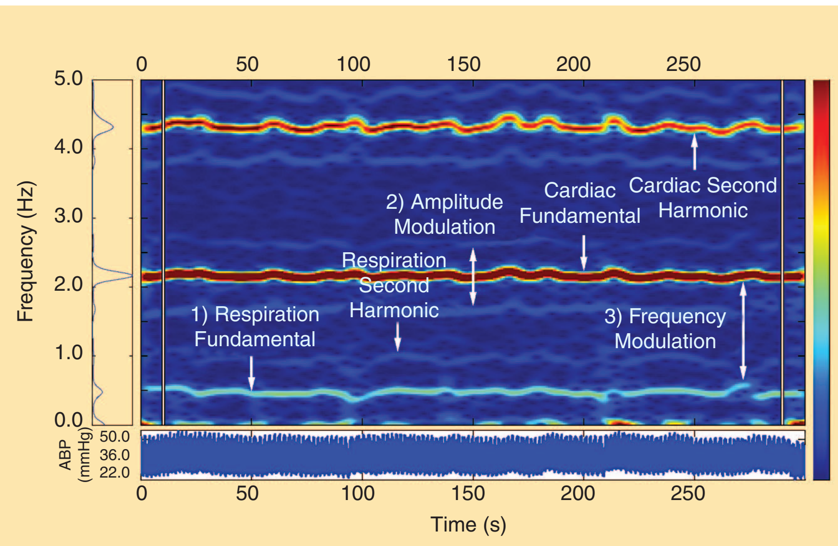
An Effective Color Scale for Simultaneous Color and Gray-Scale Publications

The use of images to represent properties of signals is ubiquitous in signal processing applications. In most cases, a color scale is used to represent a single dependent variable as a function of two independent variables. Figure 1 shows a typical example of a spectrogram that represents how the signal power is distributed across time and frequency. The image is pseudocolored with a common color scale that roughly resembles a rainbow. This article describes a new color scale that has several advantages over existing color scales such as the one shown in Figure 1.



[FIG1] Spectrogram of an arterial blood pressure signal.

Many conference proceedings and journal publications are now distributed in both printed and electronic forms. Gray scale is required to unambiguously represent images in printed publications. However, color is increasingly available for electronic publications at no additional cost. Unfortunately, most color scales are distorted when converted to gray scale. This diminishes the ability of the image to convey critical information and can cause ambiguities. To facilitate publications in both forms simultaneously, this article proposes a color scale that appears as a monotonic gray scale in printed form and significantly enhances the image resolution when viewed in color.

Luminance (or gray scale) is crucial to discern spatially high-frequency features and specific forms in images, such as peaks, ridges, and valleys [1], [2]. However, the addition of color can improve the accuracy with which we can discern specific values from images [3].

Although some commercial tools are available to tune a color scale to enhance the features of interest in a specific image [2], in most applications and publications, a general-purpose color scale is used. An algorithm for finding an optimal color scale was proposed in [4], but this color scale was inferior to a linearized gray scale in a lesion detection task for brain images. The color scale proposed here is easier to implement, has fewer design constraints, and may have better image resolution. A nine-level color scale with monotonic luminance was described in [5], but it is not clear that this color scale has any advantages over other current color scales with monotonic luminance.

Selecting a single color scale for publications is difficult, partly because most devices (e.g., monitors, color printers) have a different gamut of colors that they are capable of displaying. This is also difficult because the appearance of a color depends on the colors in the neighboring regions of the image. Thus, the best color scale depends on the image properties, the features of interest, and the gamut of colors available for the display medium.

SELECTING A COLOR SCALE

Four design principles guide the selection of an effective color scale. First, to maximally enhance the image resolution when displayed in color, the color scale should cover as much of the range of available colors as possible,

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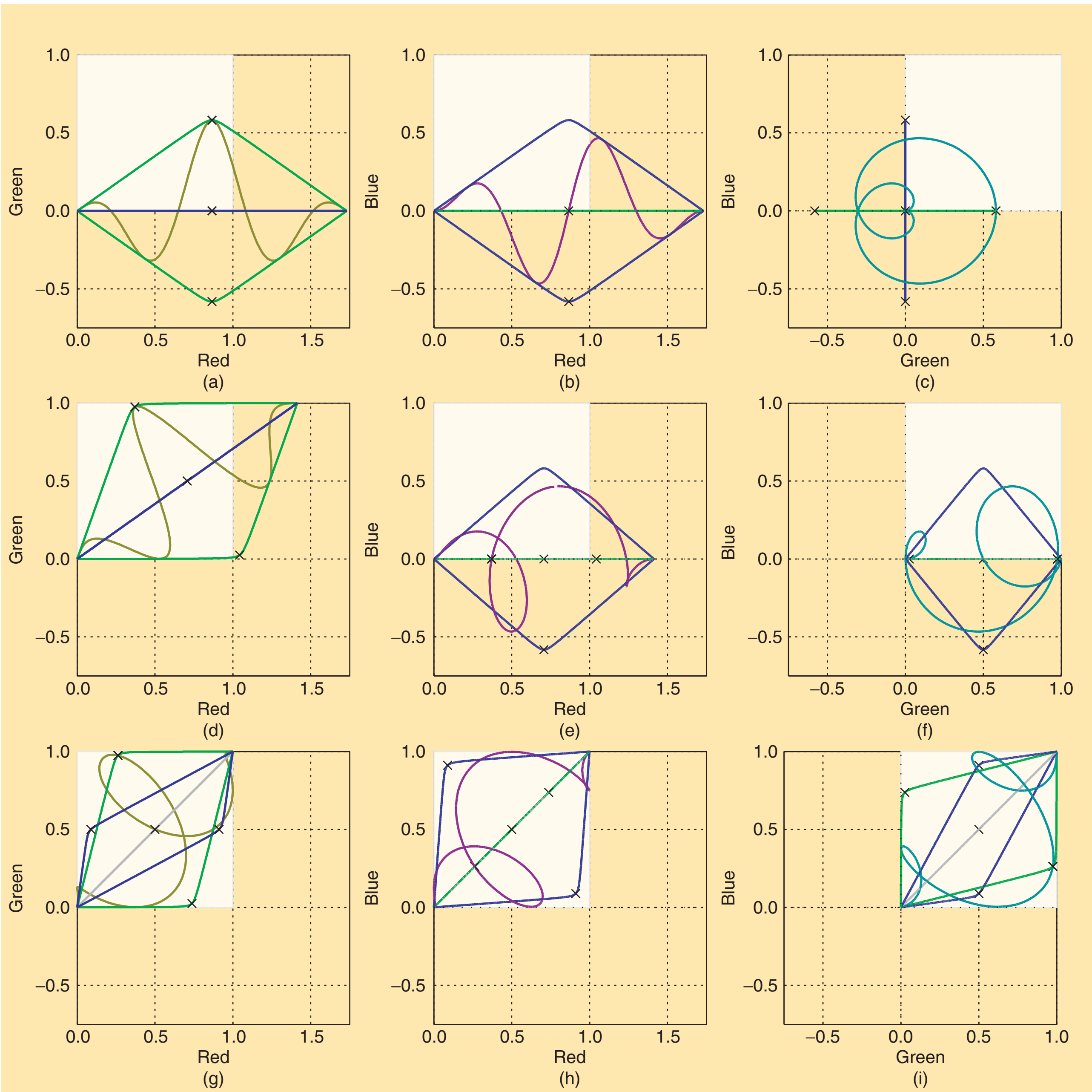
subject to the constraints that the luminance increases monotonically (for gray scale publications).

Second, neighboring colors throughout the scale should be as distinct as possible. This is motivated in part by the linear separation theory, which states that objects can be more easily identified when their color cannot be formed by a linear combination of the neighboring colors [6]. For example, it is more difficult to identify an orange object surrounded by red and yellow than an object surrounded by red or yellow colors alone.

Third, the perceptual difference between two colors should be approximately proportional to the difference between their positions along the color scale [7]. This is difficult to achieve in practice because different devices render colors differently and because most common computer packages, such as MATLAB, do not permit the specification of colors in perceptually uniform color spaces. At the very least, similar colors should not appear at points that are far apart on the color scale.

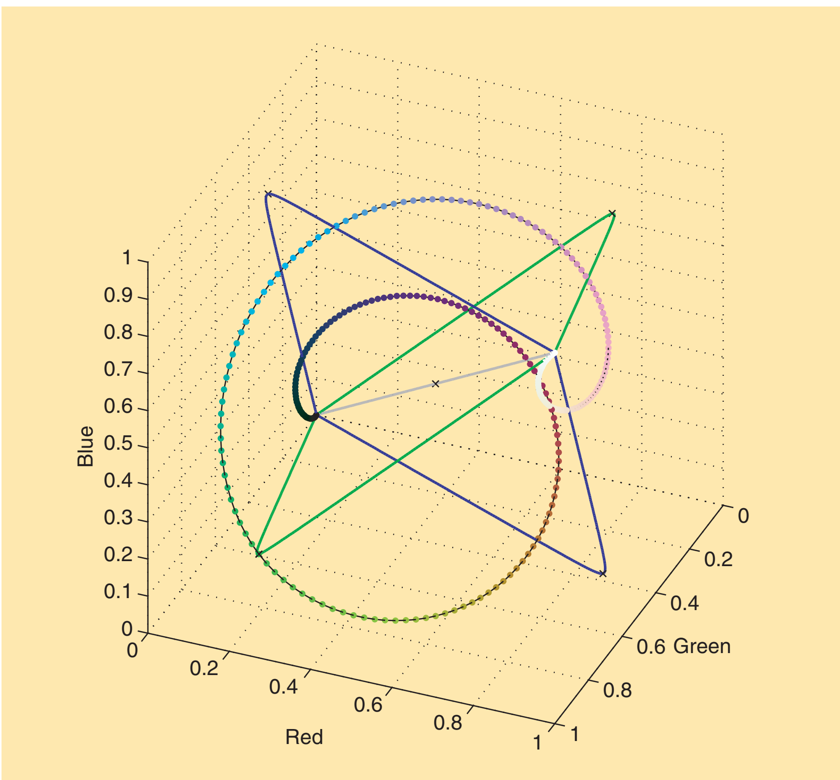


[FIG2] Projections of the color spiral onto (a), (d), and (g) the red-green, (b), (e), and (h) red-blue, and (c), (f), and (i) green-blue planes in the RGB color space. The window functions for the initial green and blue values are shown by the green and blue boundaries, respectively. (a), (b), and (c): The initial windowed complex sinusoid. (d), (e), and (f): Projections after the first rotation around the blue axis. (g), (h), and (i): Projections after a second rotation around the green axis. The projection onto the unit cube is shown by the gray region. After the second rotation, all three projections show that the color spiral is confined to the unit cube.

Fourth, the color scale should be intuitive. Humans perceive color in three dimensions because we have three types of receptors that sense light with sensitivities near blue, yellow-green, and yellow-red frequencies. However, we perceive and process color images in terms of luminance (one dimension) and color (two dimensions). Although there are many possible representations of color, people most naturally perceive color in terms of its saturation and hue. Saturation is a measure of how pure or vivid the color is, as compared to a gray of the same luminance. Hue is the actual shade or tint of the color and usually corresponds to a specific wavelength of light in the visible spectrum (i.e., the rainbow). The luminance, saturation, and hue should vary smoothly along the color scale. People can also perceive color in terms of opponent color channels that consist of blue-to-yellow and red-to-green variations [1], [8]. Thus, the color scale will have greater perceptual color resolution if it contains a blue-to-yellow transition and a red-to-green transition.

PROPOSED COLOR SCALE

It is generally accepted that the best color scales have monotonic luminance and cycle through a variety of hues [1]. In most three-dimensional (3-D) color spaces, these scales appear as spirals. There is little in the literature to guide the mathematical construction and implementation of these color scales. A particularly simple and efficient spiral can be formed out of the familiar complex sinusoid that is the basis of linear systems analysis and spectral signal analysis.



[FIG3] Trajectory of the spiral color scale through the RGB unit color cube.

Suppose that we specify colors in terms of red, green, and blue (RGB) values that range from zero (off) to one (maximum intensity). The gamut of possible colors is confined to the unit cube within this color space. Define t as an independent index to the color scale that monotonically increases from zero to a maximum value of $\sqrt{3}$, the Euclidean distance from black (RGB = 000) to white (RGB = 111) in the unit color cube. Define the initial RGB values as follows:

$$r_0(t) = t$$

$$g_0(t) = w(t)\cos\left(p\frac{2\pi}{\sqrt{3}}\left(t - \frac{\sqrt{3}}{2}\right)\right)$$

$$b_0(t) = w(t)\sin\left(p\frac{2\pi}{\sqrt{3}}\left(t - \frac{\sqrt{3}}{2}\right)\right),$$

where p is a user-specified parameter that controls the number of cycles that occur over the range of the color scale, and $w(t)$ is a window function that controls how rapidly the spiral expands and contracts. Figure 2(a), (b), and (c) shows the projections of this initial spiral on the red-green, blue-red, and blue-green planes of the color cube.

The second set of RGB values is formed by rotating the spiral counterclockwise around the blue axis by the angle given by $\theta_t = \sin^{-1}(1/\sqrt{3})$ (approximately 35.2°). This is most easily computed by converting $r_0(t)$ and $g_0(t)$ to polar coordinates, increasing the angle by θ_1, and converting them back to rectangular coordinates. This rotation does not alter the initial blue values. After this rotation, the green values are confined to the allowable range of 0–1. Figure 2(d), (e), and (f) shows the projections of the resulting spiral onto each of the three color planes.

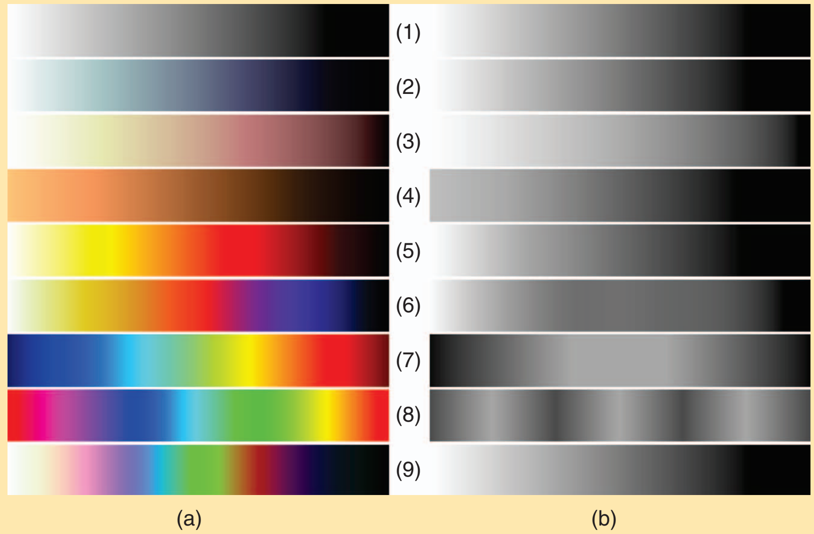
The final set of RGB values is formed by performing a second rotation counterclockwise around the green axis by 45°. This rotation does not alter the green values. After this rotation, all three projections are confined to the unit color cube. Figure 2(g), (h), and (i) shows the projections of the resulting spiral onto each of the three color planes. Figure 3 shows a 3-D plot of the spiral.

The code that implements this color scale in MATLAB is given below. The user must define the number of colors with `nc` and the number of periods (i.e., the frequency) of the complex sinusoid with `np`. A MATLAB function implementation of this color scale is available at http://bsp.pdx.edu.

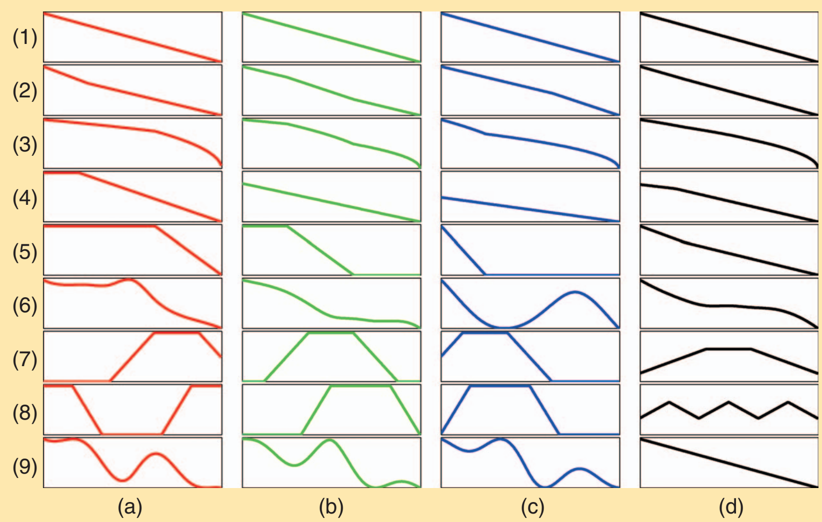
```
wn = sqrt(3/8)*[0;triang(nc-
   2);0]; % Triangular
   window function
a12 = asin(1/sqrt(3));
    % First rotation angle
a23 = pi/4;
    % Second rotation angle

t = linspace(sqrt(3),0,nc).';
  % Independent variable
r0 = t; % Initial red values
g0 = wn.*cos(((t-
   sqrt(3)/2)*np*2*pi/sqrt(3)
   )); % Initial green values
b0 = wn.*sin(((t-sqrt(3)/2)
   *np*2*pi/sqrt(3)));
   % Initial blue values

[ag,rd] = cart2pol(r0,g0);
        % Convert RG to polar
[r1,g1] = pol2cart
        (ag+a12,rd); % Rotate
        & convert back
b1 = b0;

[ag,rd] = cart2pol(r1,b1);
        % Convert RB to polar
[r2,b2] = pol2cart
        (ag+a23,rd); % Rotate
        & convert back
g2 = g1;
r = max(min(r2,1),0);
  % Ensure finite precision
g = max(min(g2,1),0);
  % effects don't exceed
b = max(min(b2,1),0);
  % unit cube boundaries
mp = [r g b];
   % Final colormap matrix
colormap(mp); % Apply to
the current figure
```

The gray scale equivalent of a color in this space is the average of the RGB intensities. Geometrically, this is the orthogonal projection from the 3-D color space onto the one-dimensional chord that spans from black (RGB = 000) to white (RGB = 111). This projection of the proposed color spiral onto the gray scale axis is equivalent to projecting $g_0(t)$ and $b_0(t)$ onto the red axis prior to the two rotations, $g_0(t) = b_0(t) = 0$. In this case, the gray scale equivalent is just a line of length $\sqrt{3}$ that initially lies along the red axis and is rotated twice to fit in the unit color cube. This is shown as the gray chord in Figure 3.

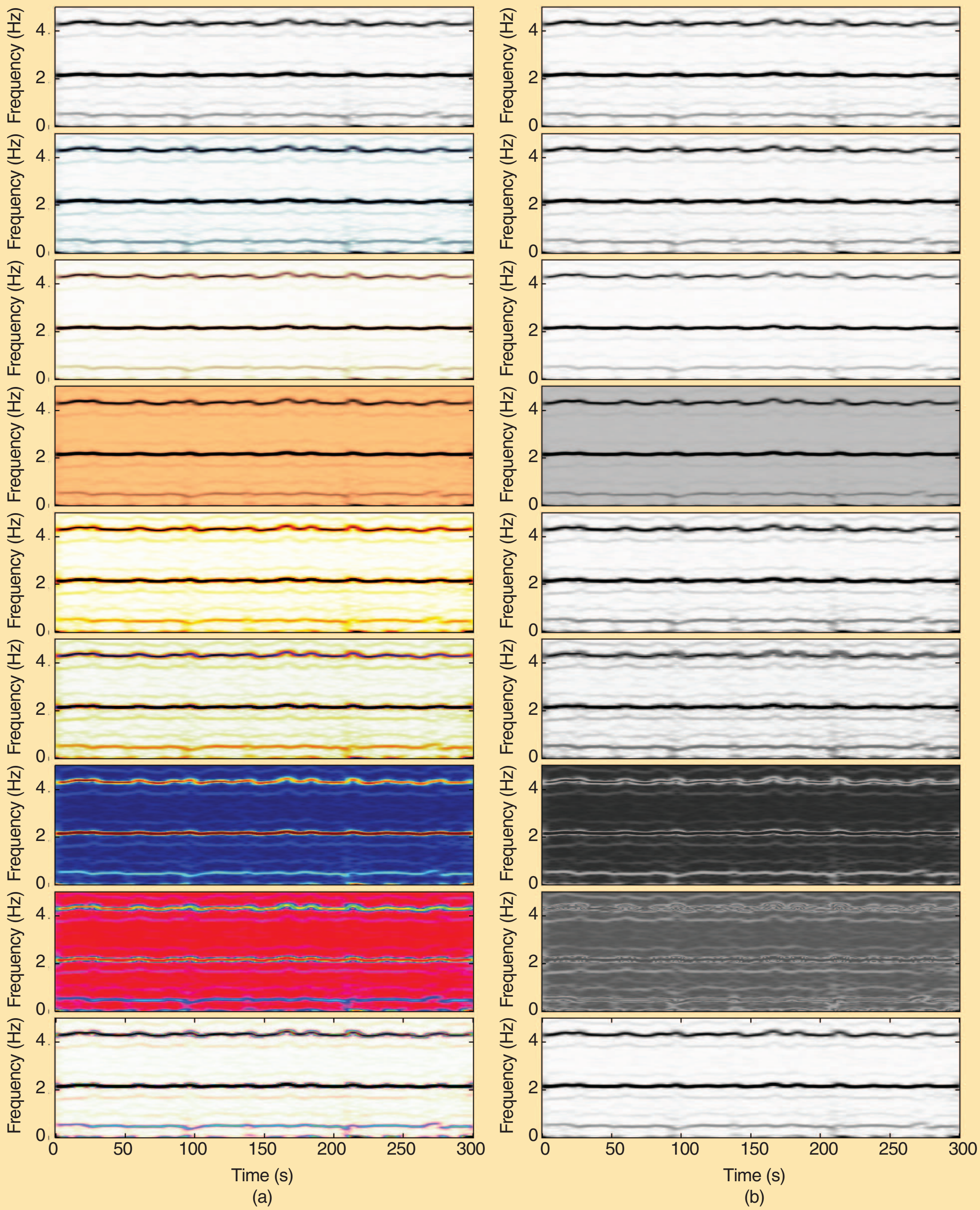
To ensure that the final color spiral fits entirely within the unit color cube, the window function must not be any greater than a triangular window function with a maximum amplitude of $\sqrt{3}/8$. Although a triangular window could be used, the slope of this function is discontinuous at the midpoint of the color scale $t = \sqrt{3}/2$. In some applications, this may create an artificial boundary in the pseudocolored image. The hyperbolic function is a good alternative that circumvents this problem. All of the examples in this article used a



[FIG4] Examples of (a) nine color scales and (b) their corresponding luminance, which would be produced in gray scale reproductions. Row (9) depicts the new color scale.



[FIG5] (a) Red, (b) green, (c) blue, and (d) luminance values of each of the nine color scales in Figure 4. Column (d) shows if the luminance is monotonic or not and, if monotonic, if the luminance is linear.



[FIG6] Spectrogram of an arterial blood pressure signal created using each of the nine color scales. (a) The spectrograms in full color. (b) The spectrograms as they would appear in a gray-scale reproduction.

hyperbolic window with a maximum value of $\max_t w(t) = 0.95\sqrt{3}/8$, This is an analytic function that prevents the appearance of artificial boundaries but closely approximates the triangular window at values that are distant from the midpoint of the color scale.

The parameter p is the frequency of the complex sinusoid, and it controls the number of periods that occur over range of the color scale. If p is too large, then similar colors may be assigned to regions that are far apart on the color scale. If p is too small, then only a small portion of the possible colors will be used, and little additional resolution will be gained by the application of color. In practice, values in the range $1.5 \leq p \leq 3.0$ offer a reasonable compromise. All of the examples in this article used $p = 2$.

COLOR SCALE PROPERTIES

The proposed spiral color scale has many nice properties and follows the four design principles discussed earlier. The spiral is designed to smoothly cycle through a variety of hues with maximum saturation, subject to the constraint that the luminance decreases linearly. When only the luminance is viewed, the color scale is identical to a linear gray scale. If a perceptual gray scale is preferred, it can be obtained by scaling the initial scale index variable t accordingly [1]. The spiral is designed such that the brightest hue of green is obtained at the midpoint of the scale. The dominant color preceding green is blue and the dominant color that follows is red. In this way, the spiral roughly resembles the familiar and intuitive rainbow color scale.

EXAMPLES

The advantages of the proposed color scale properties are illustrated in the following examples. Figure 4 shows seven popular color scales that are included in MATLAB, the color scale proposed in [5] (row 6), and the new color scale (row 9). Figure 4(a) and (b) shows how each color scale would appear in color and gray scale reproductions, respectively.

The columns of Figure 5 show the corresponding red, green, blue, and overall luminance of the color scales. Notice that two color scales that roughly resemble the natural "rainbow" spectrum (rows 7 and 8) do not have a monotonic luminance (right column). The color scales in rows 3–6 have a monotonic but nonlinear luminance. This causes a higher contrast in some regions of the color scale. Only the color scales in rows 1–2 and the new color scale have linear luminance, which ensures that gray-scale contrast is uniform over the full range of the scale. Of all the color scales with monotonic luminance, only the new color scale possesses both a linear luminance and a wide range of distinct colors to maximize the color resolution.

Figure 6 shows the spectrogram of Figure 1 for each of the nine color scales (a) and their corresponding gray scales (b). The dominant features of this spectrogram are the cardiac components (2.16 and 4.32 Hz), the cardiac sidebands due to pulse pressure variation (2.16 ± 0.45 Hz and 4.32 ± 0.45 Hz), the respiratory component (0.45 Hz), and the second respiratory harmonic (0.90 Hz). Each color scale is able to represent the amplitudes of these four components and the background intensity with different resolutions. The color scale in row 2 does not have any better resolution than the linear gray scale in row 1. The color scales in rows 3–6 show the low-amplitude harmonics and cardiac sidebands less clearly than the linear gray scale. One can most clearly discern the amplitudes of each of the components from the color scale in row 7, but the gray-scale version of this figure is more difficult to analyze due to the ambiguities caused by the nonmonotonic luminance. The amplitudes of each of the four dominant features can be discerned clearly from the new spiral color scale (bottom row) without compromising the resolution of the gray scale version.

[THIS ARTICLE PROPOSES A COLOR SCALE THAT APPEARS AS A MONOTONIC GRAY SCALE IN PRINTED FORM AND ENHANCES THE IMAGE RESOLUTION WHEN VIEWED IN COLOR.]

SUMMARY

Pseudocolored images are used in many signal processing applications to represent signal properties as a function of two independent variables, such as time and frequency. The color scale described in this article can be used to unambiguously represent these images in printed gray-scale publications as well as full color electronic publications. This color scale also allows for correct interpretation by people with common types of color blindness, which accounts for approximately 10% of the male population and 1% of the female population.

While it may be possible to obtain a better resolution with a color scale that is designed for a particular image on hand, the proposed color scale works well in many applications where the user does not have the time or resources to tailor the color scale to a specific image. The proposed color scale is also easy to implement and has an intuitive interpretation in that it cycles through a sequence of hues that roughly resembles the familiar rainbow.

AUTHOR

James McNames has been with the Electrical and Computer Engineering Department at Portland State University since 1999, where he is an associate professor and director of the Biomedical Signal Processing Laboratory. His primary research interest is statistical signal processing with applications to biomedical engineering and semiconductor manufacturing. He has published more than 90 peer-reviewed journal and conference papers.

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