Colormap Optimization for MEG/EEG Data Visualization

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Overview

For a long time, colormaps in visualizations were overlooked and not taken into consideration. Often the default colormaps (usually jet or another rainbow colormap) were used no matter the application. Recently however, consensus started to happen among scientists about the disadvantages of such colormaps and new ones were created. MATLAB changed its default to Parula and Matplotlib followed by changing to Viridis. Influenced by these changes, new default colormaps were created for Brainstorm, a user-friendly application for MEG/EEG analysis.

To understand why this change was made, let's compare two "opposite" colormaps: one that doesn't use any colors: the gray colormap, and one that spans all the colors of the rainbow: jet (MATLAB's rainbow colormap).

Grayscale vs. jet

Pattern: The cone viewed from the top (see Figure 1) is a very clear assessment of the two colormaps. While the sides of the cone are smooth, it appears to have sharp edges when plotted with Jet. This is due to 2 reasons: the non uniform variation in lightness, and the nonlinear variation in perceived hue (the blue band, for example, is much wider than the yellow band).

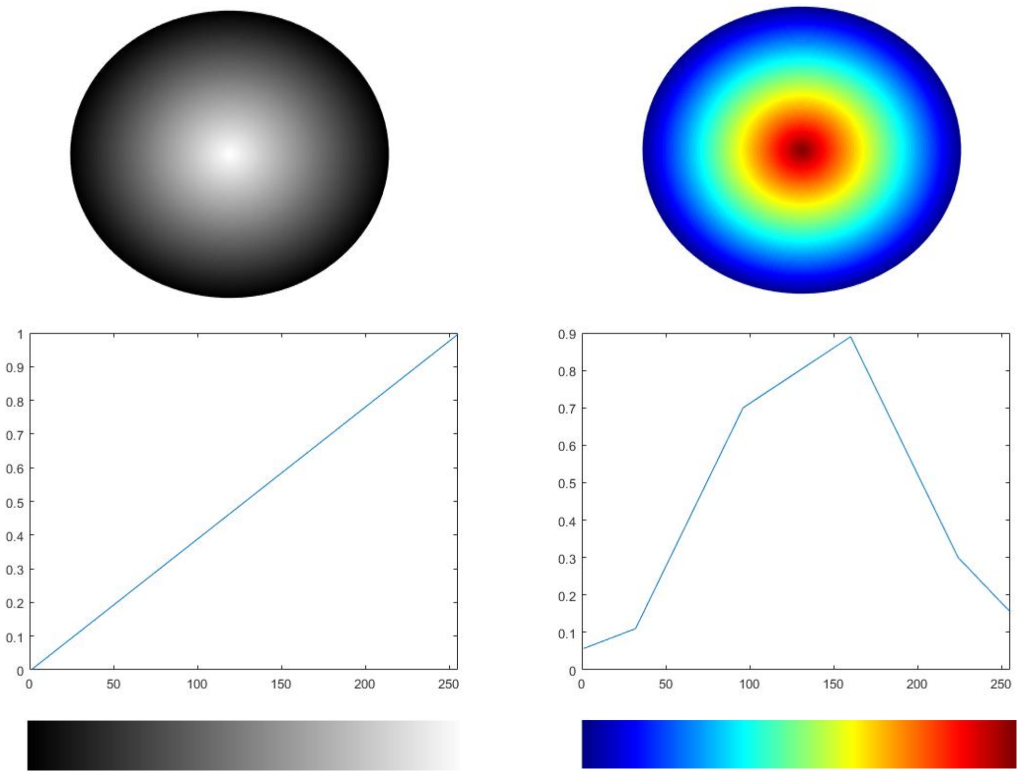

Figure 1. *A view from the top of a cone with a uniform slope plotted with the grayscale colormap (upper left) and with jet (upper right). The lightness profile and the colorbar of each colormap are shown below.*

Ordering: While the gray colormap gradually changes in lightness, jet confuses viewers because the ordering of the spectral colors that it uses is not perceptual. This can require more effort and time to interpret the visualization.

Contrast: The human visual system is more sensitive in its response to lightness variation than to color variation. While jet does have variance in lightness, it's not linear and there is a part with a very small slope that includes cyan, green, and yellow (Figure 1), which makes it harder to discriminate between regions coded in these colors. This is illustrated in Figure 2 where details are much clearer with the gray colormap than with the jet colormap, especially at lower contrast. This is even further illustrated in Figure 3, where the original image is split into two images: one image presents the luminance information and the other presents the residual chromatic information. Most of the spatial details can be obtained from the luminance image alone.

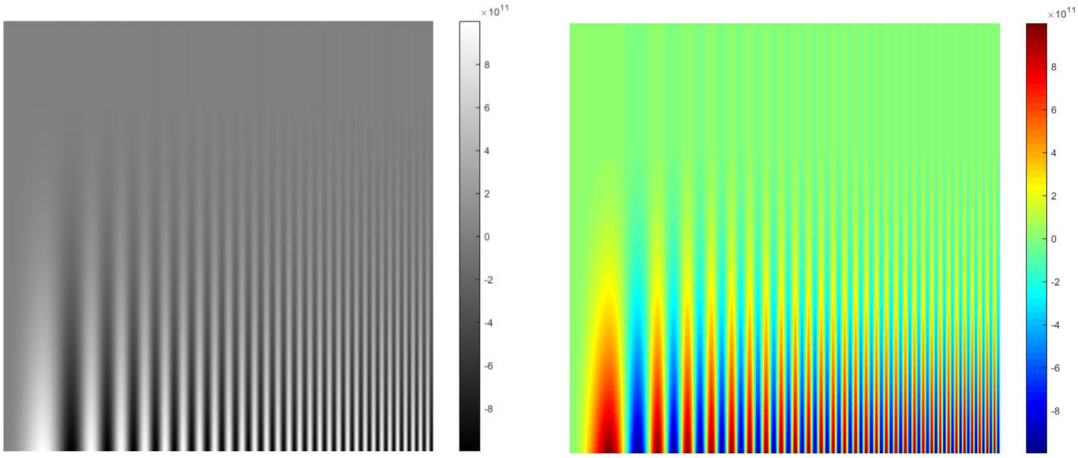

Figure 2. *Sinusoidal signal with frequency that increases to the right and amplitude that increases from top to bottom, plotted with the gray-scale (left) and with jet (right).*

Figure 3. *Illustration of the spatial properties of color vision: (a) original image, (b) luminance information only, (c) chromatic information only.*

Image credit: Fairchild, M. D. (2013). Color Appearance Models. Copyright John Wiley & Sons. Used with permission.

Resolution: Color is usually coded in 3 dimensions, but for a complete specification, 6 dimensions are required: brightness, lightness, colorfulness, saturation, hue, and chroma. However, it is often sufficient to specify only lightness, chroma, and hue. The gray colormap uses only lightness information, while jet relies mostly on hue. To maximize a colormap's perceptual resolution, it's best to make use of all 3 attributes.

Visual Illusions: The grayscale colormap is susceptible to simultaneous contrast which changes the appearance of colors and shades based on their surroundings (see Figure 4). Sharp variations in hue can minimize this effect. As a result, rainbow colormaps are better at preserving exact quantities, but only in certain parts of the colormap.

Figure 4. *Simultaneous contrast effect in a grayscale color map. All the rectangles represent the same shade of gray even though they look different.*

To understand why these phenomena take place and how can we choose colors to combine the advantages and avoid the disadvantages of both colormaps, we need to understand how color vision in the brain works.

Color Vision

Color is encoded in the brain using both energy and wavelength of light. When light hits the eyes, three types of receptors, each sensitive to a part of the visible spectrum (long, medium, and short wavelengths), transform the spectral power distribution on the retina into a three-dimensional signal. This signal is then sent to the brain for processing.

In 1874, Ewald Hering, one of the founders of modern visual science, suggested that there were two pairs of opponent processes underlying human color vision. This is in contrast with the fact that there are only three types of receptors in the eye. He noted that red and green as well as blue and yellow seem to oppose each other, just like black and white. His theory was at first resisted by many leading scientists in the field, until the middle of the twentieth century, when a lot of support from quantitative data and research began to back it up. This theory is now developed into what's called the modern opponent theory of color vision. To demonstrate this, fixate on the black spot in the center of the square in Figure 5 for a few seconds, and then fixate on the black spot in the uniform white area. Note that the afterimage of red is green, green is red, yellow is blue, and blue is yellow.

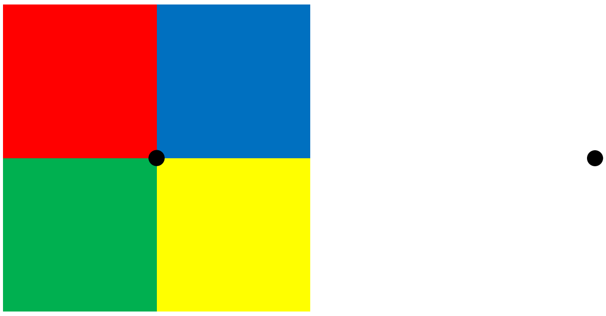

Figure 5. *Stimulus for the demonstration of opponent afterimages.*

The neural "wiring" which explains opponent responses encoding in the brain is included in Figure 6. The first stage is when light hits the three receptors, which produces a spectral responsivity relative to each receptor type. Next, instead of the three signals being transmitted directly to the brain, they are encoded into opponent signals:

- The summation of the outputs of all three cone types (L + M + S) produces an achromatic response (the black and white channel).
- Differencing of the cone signals (L − M + S) produces the red–green opponent signal.
- Differencing of the cone signals (L + M − S) produces the yellow–blue opponent signal.

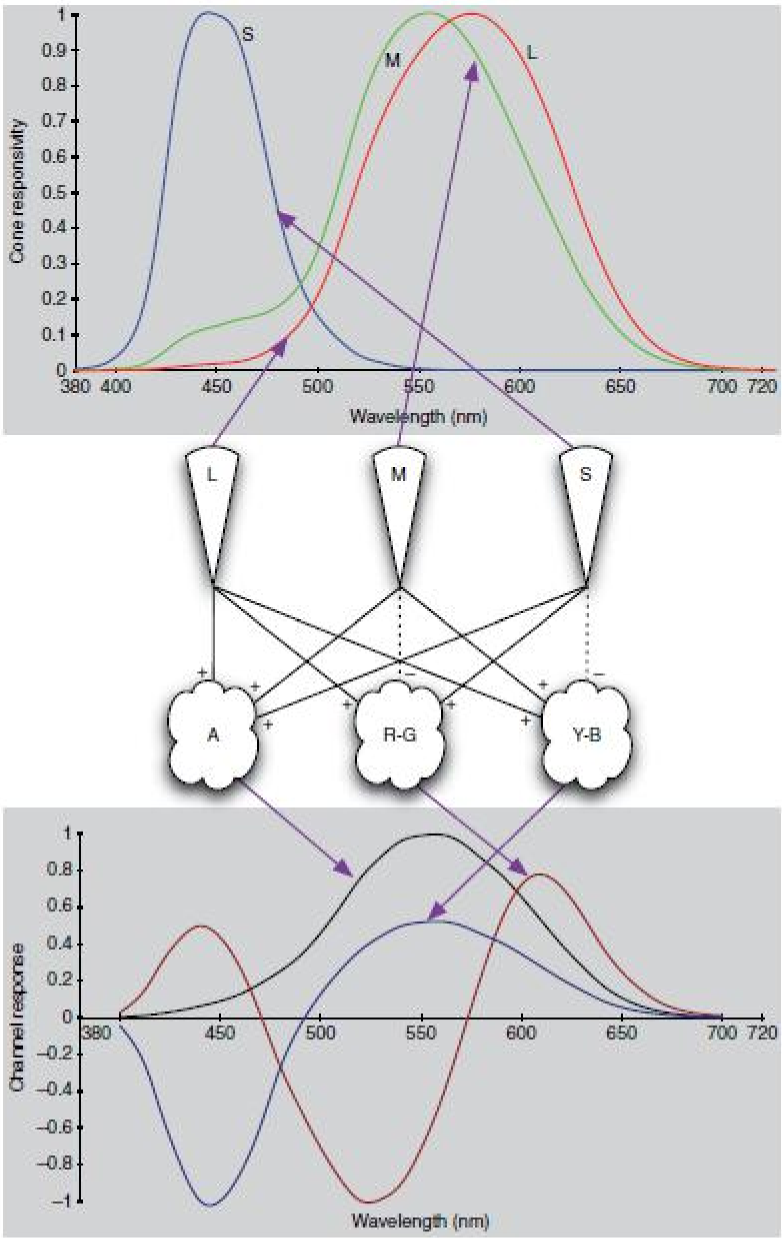

Figure 6. *Schematic illustration of the encoding of cone signals into opponent color signals in the human visual system*

Image credit : Fairchild, M. D. (2013). Color Appearance Models. Copyright John Wiley & Sons. Used with permission.

The transformation from trichromatic signals to the opponent signals has an advantage of decorrelating the color information and thus allowing more efficient signal transmission and reduction of noise. The importance of this transformation for color appearance is that it needs to be accounted for in the formulation of color models. New color models were formed that incorporate the encoding of color information through the opponent channels along with the adaptation mechanisms before, during, and after this stage. These models define colors much better than the RGB model, which considers only the trichromatic response of the three cone types.

Color Models

A color appearance model must include predictors of at least the three attributes of lightness, chroma, and hue. This allows the specification of colors in a standard way. A color model is a specification of a coordinate system where each color is represented by a single point.

CIECAM02 is a color appearance model designed by the International Commision on Illumination as an attempt to accurately model human color perception. It defines correlates for yellow-blue, red-green, brightness, and colorfulness. However, this is still insufficient. To create a colormap by drawing a line through a color space, we need the space to be perceptually uniform. This means that distance between colors in color space should match the distance judgements that we perceive. Two colors that are distance d apart should look as discriminable as any other pair of colors that are the same distance apart. This is very important for visualization because color distance often encodes meaning.

An effort to combine the appearance scales of CIECAM02 with the desired predictions of uniform color differences, resulted in the CAM02-UCS colorspace. CIECAM02-UCS defines color in terms of human opponent color processing: lightness (the J axis), redness-to-greenness (the a axis), and blueness-to-yellowness (the b axis).

RGB color space is not perceptually uniform, and so a colormap created in it would not have uniform perceptual distances between its colors. A perceptually uniform color space should thus be used when creating visualization color scales. One excellent tool for creating colormaps in the CIECAM02-UCS space is the **viscm** tool made by Nathaniel Smith and Stefan Van der Walt. This tool also maps the colors of the created colormap to the sRGB gamut which is used by most modern monitors. The gamut of a device is the range of colors that can be produced by the device as specified by its corresponding colorspace.

Choosing a Colormap

After choosing the right color model and using the 3 dimensions of color to create a colormap, there are a few more things to consider:

Reflect the data: The point of pseudo-coloring is to make the complicated data much faster and easier to understand. Just by looking at it, we should be able to decipher the pattern of the data and approximate the intensity at each point. If the data goes from 0 to a 100, the colormap should go from one color to another "opposite" color. If the data has a critical point we wish to distinguish, like having negative and positive values, with 0 as the critical value, the colormap should be able to distinguish between those two parts, by having two different colors, for example, one for each part.

3D Visualizations: For 3D visualizations, the colormap should not span different lightness profiles, which means it should be isoluminant. The reason is that, for 3D visualizations, shading would interfere with the colors, making them look more or less bright. Using an isoluminant colormap will make sure that we are basing our judgment only on the differences in hue and chroma and not on the differences in lightness. However, since differences in lightness are much better perceived than differences in hue and chroma, an isoluminant colormap is poor in contrast and harder to analyze.

Colorblind Viewers: Color vision deficiency (CVD) affects more than 4% of the population and leads to a different visual perception of colors. For most color-deficient viewers, it is hard to make the distinction between red and green. An easy way to account for this is to avoid using those two colors in the same colormap.

Intuition: To create a universal sense of understanding for visualizations, it is good to consider the application and choose the colors accordingly. Like choosing light colors for high values and dark colors for low values, blue for "cold" and red for "warm".

Appeal: To make the visualization pretty, it's good to choose colors that are in harmony together. There are different types of harmony rules that will make it easier to choose the colors of a colormap.

Results

To improve the visualizations in the Brainstorm software, an open-source application dedicated to the analysis of brain recordings, the factors mentioned above were considered. A general-purpose colormap that works well in all situations is a difficult task. That said, different default colormaps should be specified for different types of visualizations. In many of the visualizations, the default was the jet colormap, which is a type of rainbow colormap. Although Jet might be pleasing because it is always flashy and colorful, it has some well documented disadvantages when used with general-purpose data visualization. It has no intuitive ordering, hides some detail, and falsely creates edges and patterns that don't exist in the underlying data. As a result, new default colormaps were designed for Brainstorm that incorporate these characteristics. The new colormaps are created using the viscm tool; they are perceptually uniform and use linear lightness profiles. Below are a few visualizations in Brainstorm using the new default colormaps and the old ones, for comparison:

Power Spectral Density

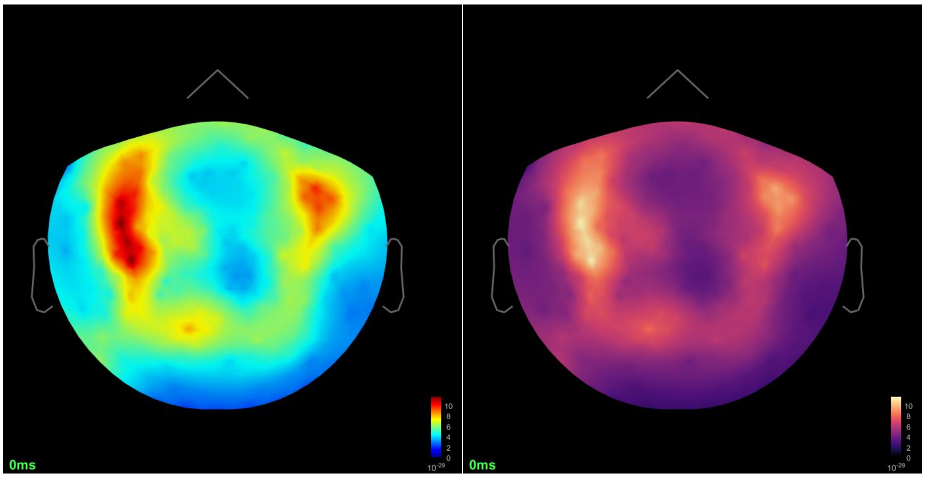

Figure 7. *Power Spectral Density mapped with jet (left) and with magma, the new default (right).*

Time Frequency Maps

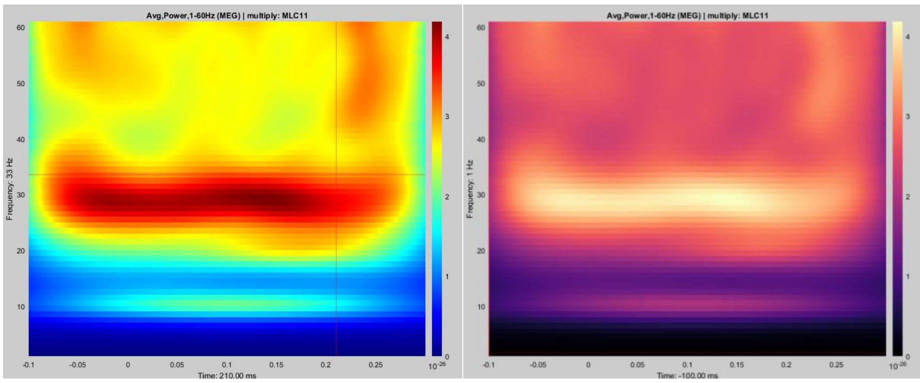

Figure 8. *Time Frequency mapped with jet (left) and with magma (right).*

Sensor Topography

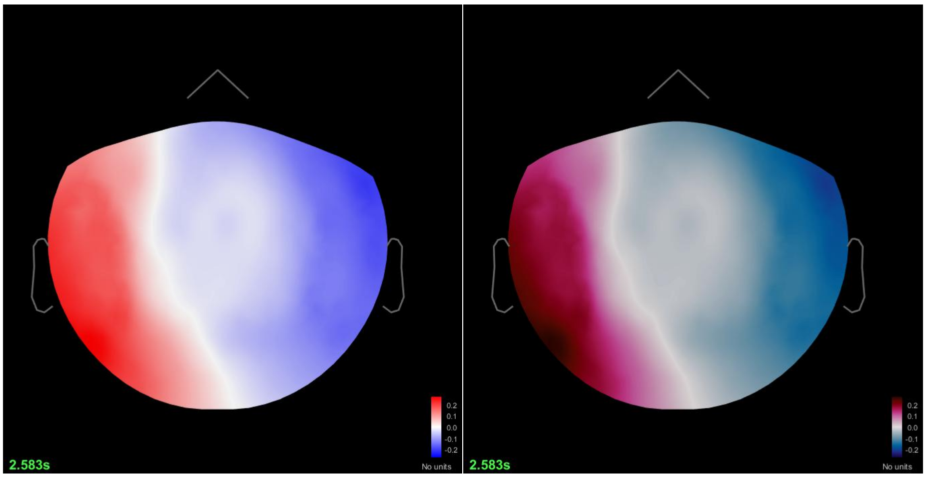

Figure 9. *Power Spectral Density mapped with rbw (left) and with the new default (right).*

Source Estimation

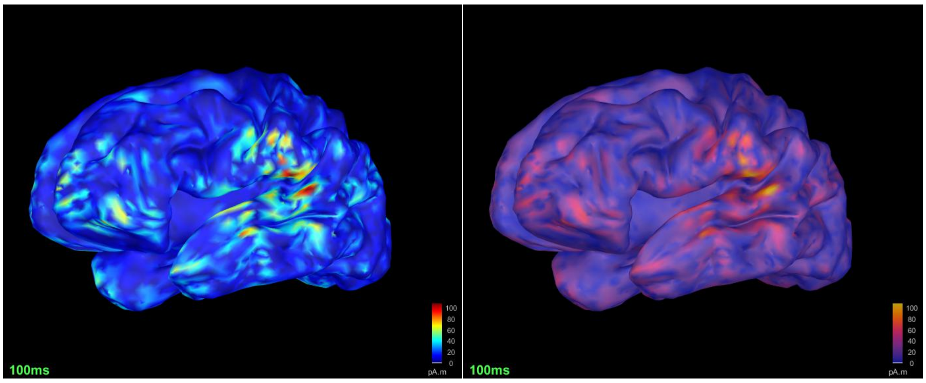

Figure 10. *Source Estimation mapped with jet (left) and with the new default (right).*

Phase Amplitude Coupling

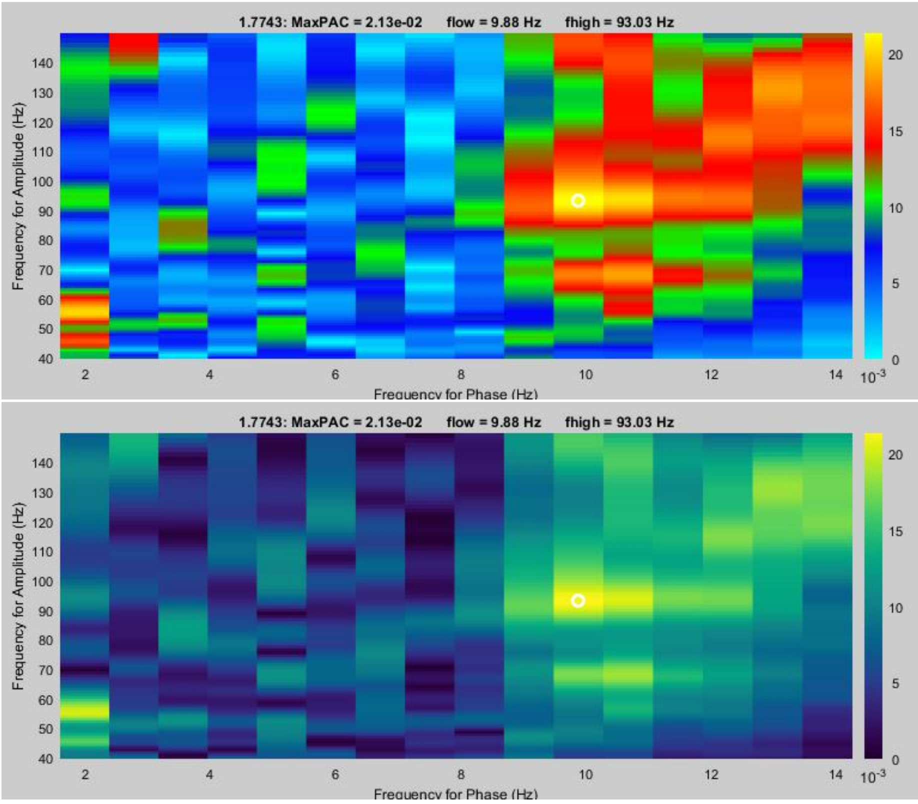

Figure 11. *Phase Amplitude Coupling (PAC) mapped with a rainbow colormap (upper image) and with the new default (lower image).*

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