Visualization of multi-channel images using differences in human perception of brightness and chromaticity

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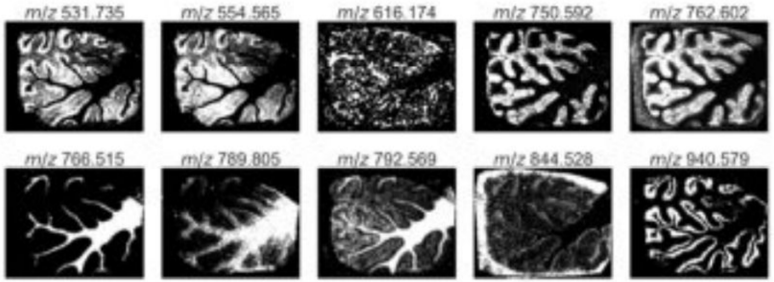
Multi-channel images

- Multi-channel image model:

  $\mathbf{c} : \Omega \rightarrow \zeta$, where is a rectangular discrete lattice $\Omega \subset Z^2$ is the domain of definition, and $\zeta \subset R^n$ is the range of values, n — number of image channels.

- Examples
  - Regular RGB photography
  - Earth Remote Sensing (multi- and hyperspectral imagery)
  - Mass Spectrometry
  - Medical Image Analysis
  - Astrophysical Data Analysis
  - Hidden layers of neural network models

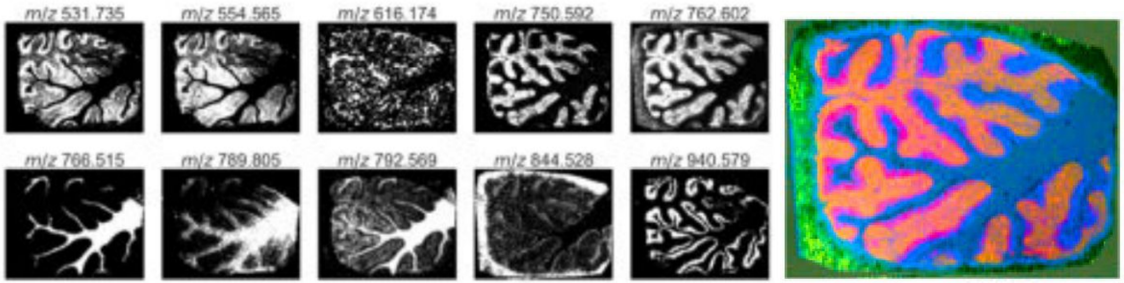
https://en.wikipedia.org/wiki/Hyperspectral_imaging



Mass spectrometry data

Visualization of multi-channel images

- The optimal number of channels of the observed image that can be perceived by a human = **3**.
- The objective of multichannel image visualization is to transform a multichannel image into an image with a reduced number of channels while maximally preserving perceptually relevant information.



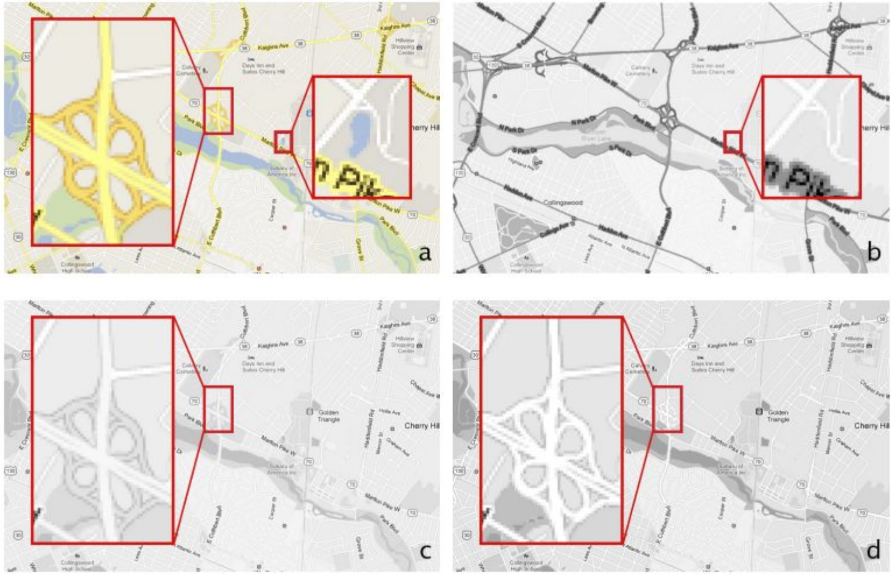
Visualization of mass spectrometry image of chimpanzee cerebellum slice.

A. Sarycheva, A. Grigoryev, D. Sidorchuk, G. Vladimirov, P. Khaitovich, O. Efimova, O. Gavrilenko, E. Stekolshchikova, E. N. Nikolaev and Y. Kostyukevich, "Structure-Preserving and Perceptually Consistent Approach for Visualization of Mass Spectrometry Imaging Datasets," Analytical Chemistry. 2020.

A portrait of a supernova. X-ray emission is rendered in blue and cyan, while red and pink correspond to infrared radiation. Sulfur emission, heated to temperatures sufficient for visibility in the optical spectrum, is depicted in green.
https://www.esa.int/ESA_Multimedia/Images/2024/03/Marvel_at_stunning_echo_of_800-year-old_explosion

Properties of visualization methods

1. *Consistency:* any initially **spectrally** close pixels will have similar intensities in the resulting image
2. *Preservation of local contrast:* difference in the values of two **spatially** close pixels will be preserved in the resulting image
3. There are methods that guarantee consistency preservation (e.g. based on PCA), but complete preservation of local contrast is generally impossible.



Different RGB-to-greyscale visualizations with **local contrast loss.**

Original image

Visualization **with local contrast loss** by PCA-based method

Visualization with **violation of consistency**

Types of visualization methods

Methods that guarantee consistency:

- Visualization based on dimensionality reduction methods: both linear (PCA) and nonlinear (UMAP)
- These methods operate on the principle of independent pixel-by-pixel mapping from the original n-dimensional value space to the resulting m-dimensional space, where m = 1 or 3. Due to which consistency is guaranteed

Methods aimed at preserving local contrast

the gradient of a multichannel image **c** at a pixel (x,y) is determined through the largest eigenvalue and the corresponding eigenvector of the structural tensor C(x,y):

$$C(x,y) = (\nabla c(x,y))^T \nabla c(x,y) \qquad \nabla \mathbf{c}(x,y) = \begin{bmatrix} \frac{\partial c_1(x,y)}{\partial x} & \frac{\partial c_1(x,y)}{\partial y} \\ \vdots & \vdots \\ \frac{\partial c_n(x,y)}{\partial x} & \frac{\partial c_n(x,y)}{\partial y} \end{bmatrix}$$

$$\tilde{\nabla}\mathbf{c}(x,y) \in Eig_{\Lambda}, \quad |\tilde{\nabla}\mathbf{c}(x,y)| = \sqrt{\Lambda/n},$$

where Λ is the largest eigenvalue of C(x,y), Eig_{Λ} is the eigenspace corresponding to Λ, n is the number of channels of the multichannel image.

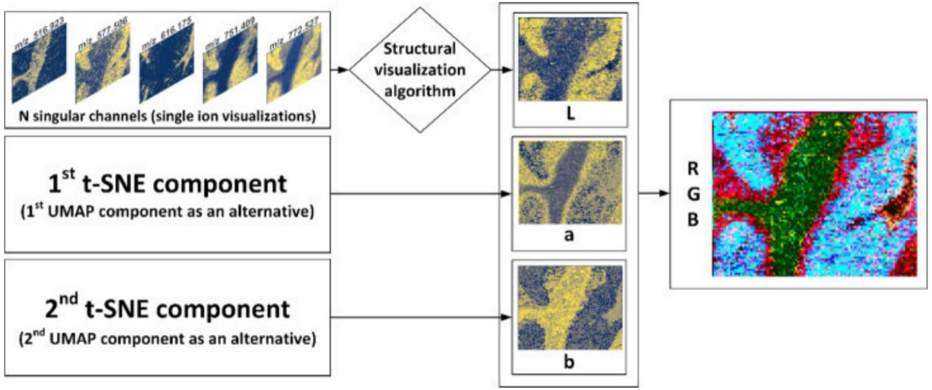
$$\sum_{x,y\in\Omega} E(\nabla\mathbf{r}(x,y), \tilde{\nabla}\mathbf{c}(x,y)) \to \min_{r}.$$

Combined methods of color visualization

In the case when the output image can have 3 channels, it is possible to use methods of different types to fill them

Sokolov combined method of color visualization

- A method was proposed that is consistent in chromaticity and preserves local contrast by manipulating the achromatic (brightness) component [1]:
- The result of the contrast-preserving method is used as the brightness component (L) of the output image, and the result of the consistent method is used as the two chromaticity components of the output image (a, b):



Scheme taken from
A. Sarycheva, et al., “Structure-Preserving and Perceptually Consistent Approach for Visualization of Mass Spectrometry Imaging Datasets,” Analytical Chemistry. 2020.

- Due to such distribution, two properties of the visualization methods (consistency and preservation of local contrast) are coordinated with the functions of achromatic and chromatic contrast sensitivity of the human vision system. **Our goal is to verify that such coordination gives an advantage to the Sokolov method.**

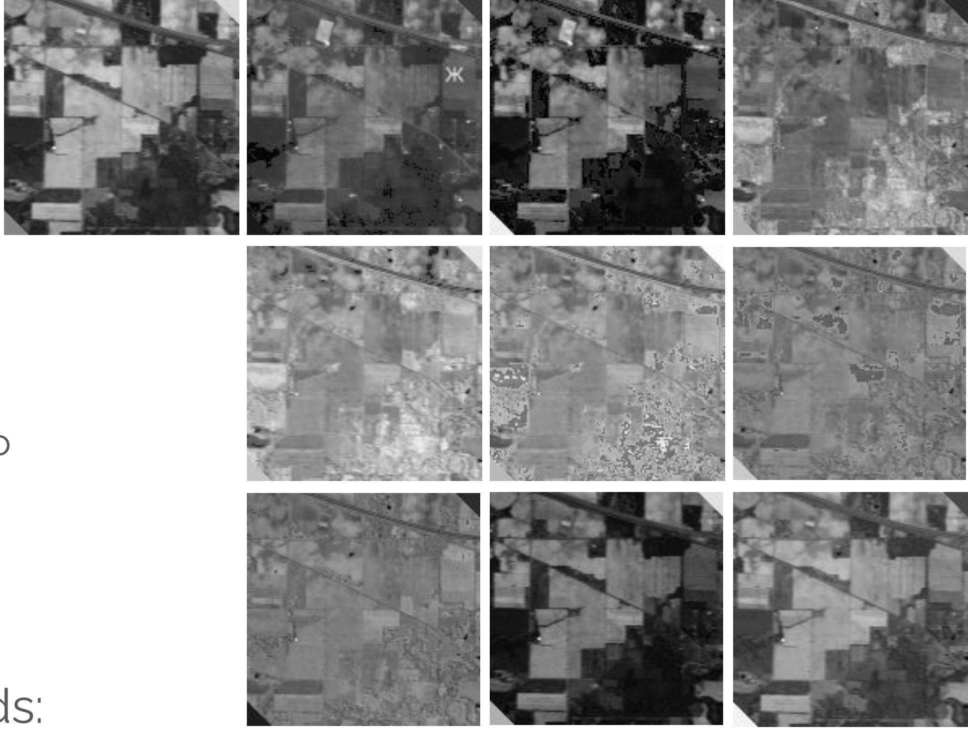
[1] V. Sokolov, D. Nikolaev, S. Karpenko and G. Schaefer, “On Contrast-Preserving Visualisation of Multispectral Datasets,” LNCS, Gerhard Goos, Ed., Cham, Switzerland, Springer Nature Group, 2010.

Setting up the experiment

- Research questions:
  - Is Sokolov's combined method superior to other known methods?
  - Does it matter which channels are used in a combined approach?
    - what if in Sokolov's method we use not Lab, but just RGB?
- The visualization is oriented towards human perception, so human studies were necessary to provide an answers
- The approach chosen was not to ask subjects about local contrast and consistency directly, but to formulate tasks that would allow indirectly assessing the corresponding properties.
  - Take a real multi-channel image as a base
  - To assess the contrast, draw letters in separate channels and ask whether the letters are visible in the resulting image.
  - For consistency assessment, select two areas, fill them in all channels either identically or differently, and ask if they are **seen** the same color as a result

Test data set

- 5 original 10-channel images were created
  - The channels of the famous Indian Pines hyperspectral image were used as a base
  - Letters of the russian alphabet were added to some input channels.
  - Corners were added to the image. On some, they were originally different, on others, they were the same as the original.
- Each image was visualized by 4 methods:
  - PCA
  - UMAP
  - Sokolov's method with RGB filling (Sokolov-RGB)
  - Sokolov's method with Lab filling (Sokolov-Lab)



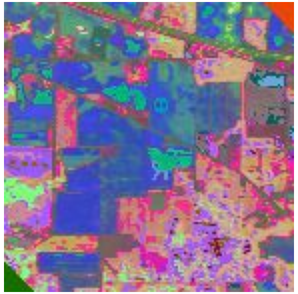
Channels of one of the created multichannel images

PCA Sokolov-Lab Sokolov-RGB UMAP

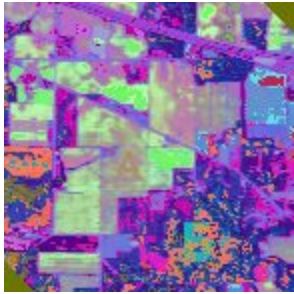
Qualitative analysis of local contrast preservation

- UMAP: global contrast is higher, but local contrast is lost in some cases

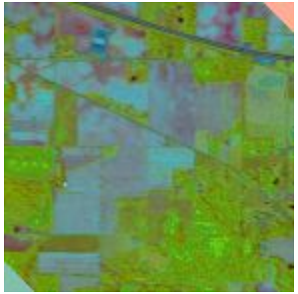

Sokolov-Lab

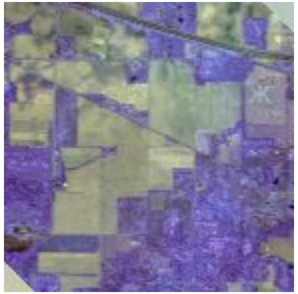

UMAP

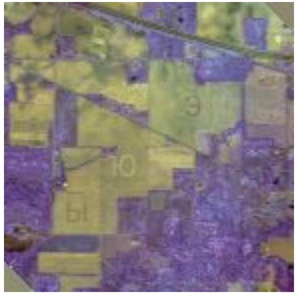

Sokolov-Lab


UMAP

- Sokolov-Lab outperforms PCA and Sokolov-RGB in terms of local contrast amplitude preservation


PCA


Sokolov-Lab


Sokolov-Lab

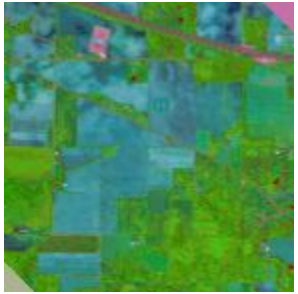

Sokolov-RGB

Qualitative analysis of consistency

- The results of PCA and UMAP in terms of consistency are expectedly superior to the results of Sokolov-RGB and Sokolov-Lab

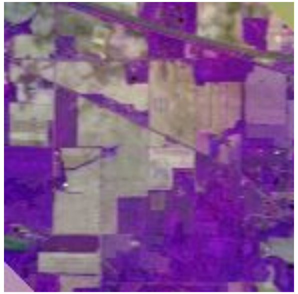
- The comparison between Sokolov-RGB and Sokolov-Lab is ambiguous

Initially different corners

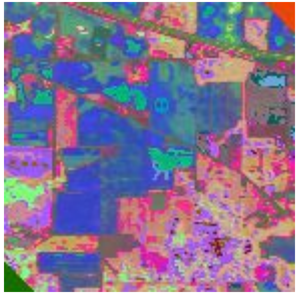


PCA

Socolov-Lab

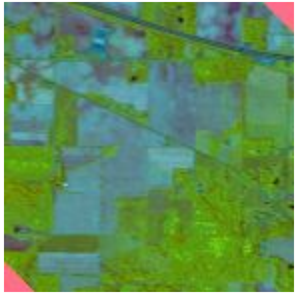


Socolov-RGB

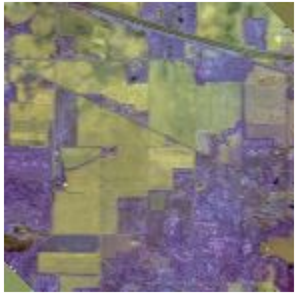


UMAP

Initially identical corners

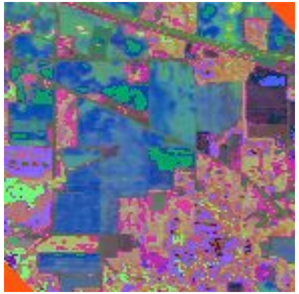


PCA



Socolov-Lab

Socolov-RGB



UMAP

Human studies design

- A special web service was created to conduct human studies.
- There are 2 types of questions asked:
    - About contrast (find the letters if any)
    - About consistency (are the corners the same color?)
- Questions are asked in random order and you have 15 seconds to answer.

Human studies results

- The tests were completed by 62 subjects, who gave a total of 2,180 answers.
- Results by contrast: the highest accuracy of answers was achieved on visualizations obtained by the Sokolov-Lab method

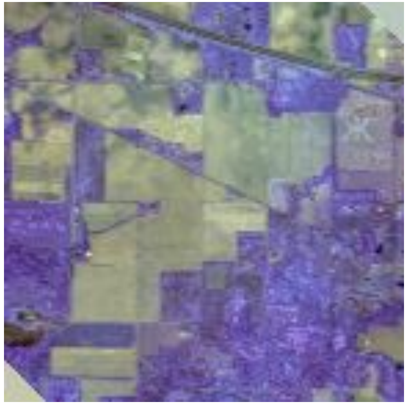
	PCA	UMAP	Sokolov-Lab	Sokolov-RGB
Accuracy	57.3%	81.1%	**91.7%**	65.5%

Accuracy of answers to the question about contrast

- Consistency results:
  - PCA (98.4%) and UMAP (96.4%) outperform Sokolov-RGB and Sokolov-Lab
  - Sokolov-RGB and Sokolov-Lab turned out to be very close (in both cases, the accuracy was 62%)

Consistency estimation issue

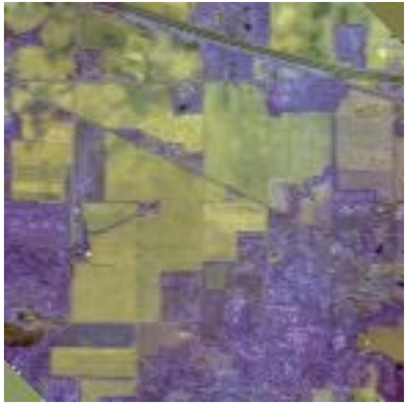
Sokolov-Lab



Sokolov-RGB

Initially, the corners are different, but were visualized as quite close. Sokolov-Lab preserved the difference in color tone and 48% of subjects were able to recognize this correctly (Sokolov-RGB accuracy is only 16%)

Sokolov-Lab



Sokolov-RGB

Initially, the corners are the same, but they were not visualized identically. Sokolov-Lab placed the error in the brightness component, Sokolov-RGB – spread it across RGB colors.

- The error in brightness was not noticed by 68% of the subjects (who correctly answered that the corners are the same).
- The error in color was not noticed by 80% of the subjects (who answered that the corners are the same).

Conclusion

- The problem of visualization of multichannel images was considered, which is fundamentally unsolvable in the sense of simultaneous preservation of local contrast and consistency.
- To determine the optimal placement of the inevitable error, a comparison of PCA, UMAP, Sokolov-RGB, Sokolov-Lab methods was conducted.
- A special data set of images was generated, human studies were designed and conducted
- As a result, it is shown that the placement of the error according to Sokolov-Lab allows obtaining the highest contrast preservation
- In terms of consistency, the Sokolov-Lab and Sokolov-RGB methods showed similar results.

Thank you for your attention!