Modelling the Distribution of Photo Receptors in the Retina in the Light of Non-Regular Sampling

Maximiliane Gruber, Jürgen Seiler, and André Kaup

maximiliane.gruber@fau.de

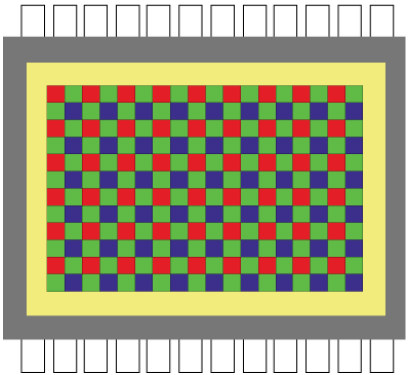
Chair of Multimedia Communications and Signal Processing

FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT

LMS

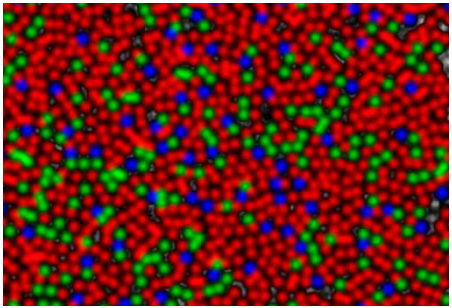
Motivation

Camera Sensor



Taken from [Adorama, 2016].

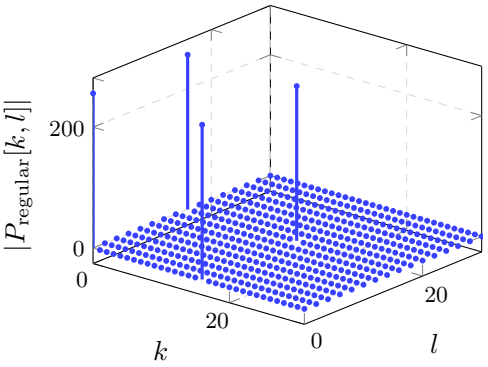
Photo Receptors in the Human Retina



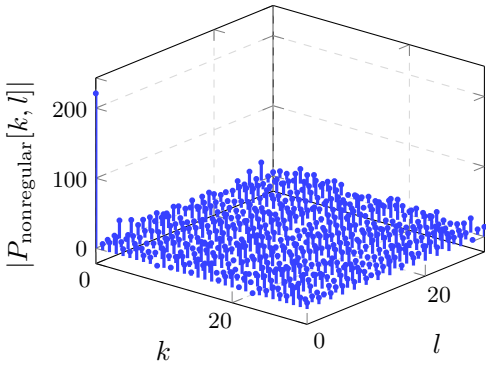
Taken from [Zhang, 2019].

Motivation

Regular Sampling



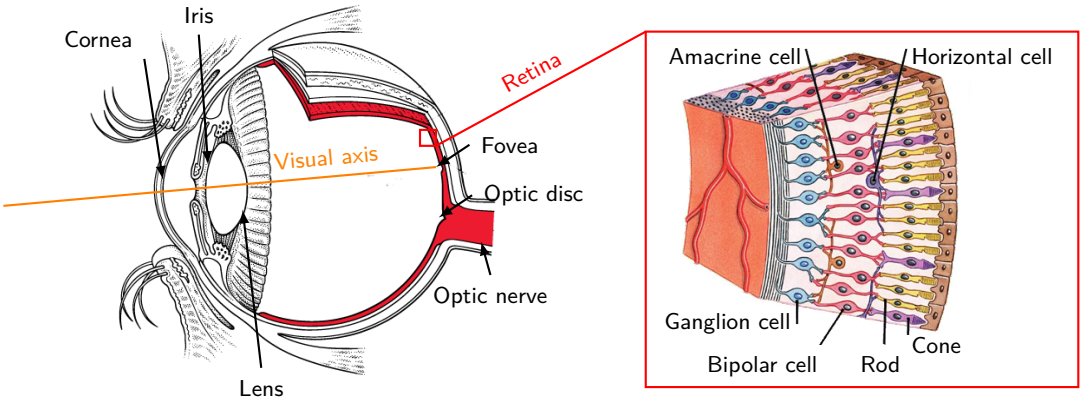
Non-Regular Sampling



Outline

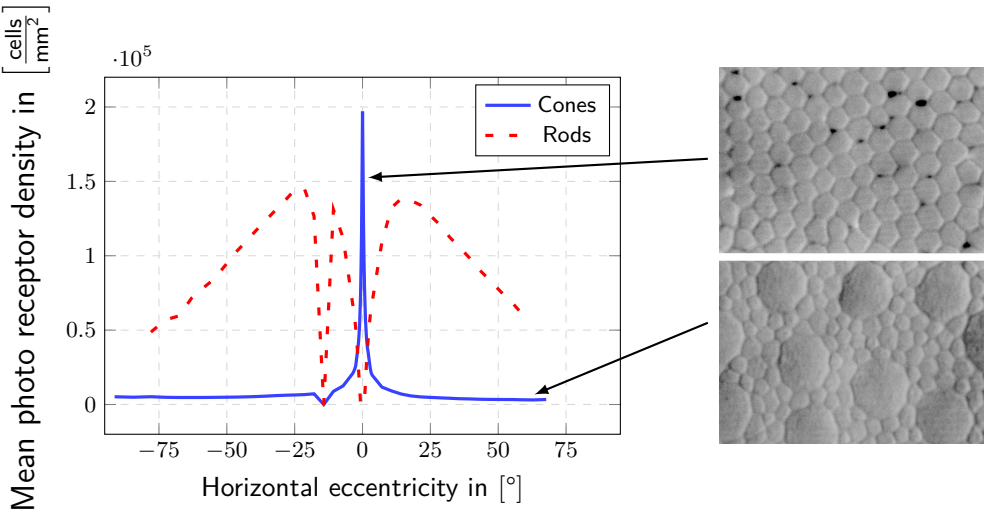
- Biological Background
- Adapted Minimum-Spacing Model
- Regular and Non-regular Sampling
- Results
- Conclusion and Outlook

Human Eye Anatomy



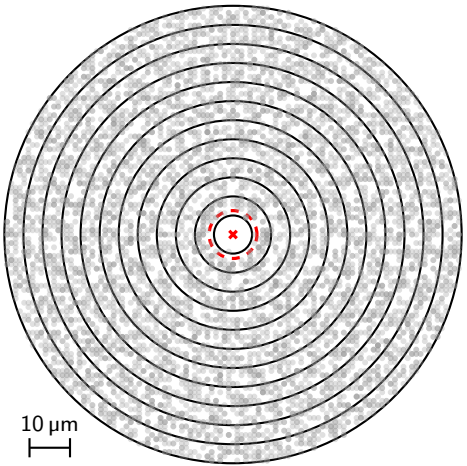
Adapted from [Saey, 2015], [Siegel, 2012].

Photo Receptor Distribution [Curcio, 1990]

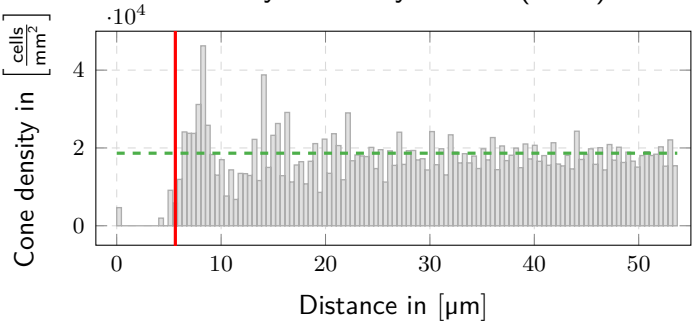


Effective Radius [Rodieck, 1991]

Autocorrelogram



Density Recovery Profile (DRP)

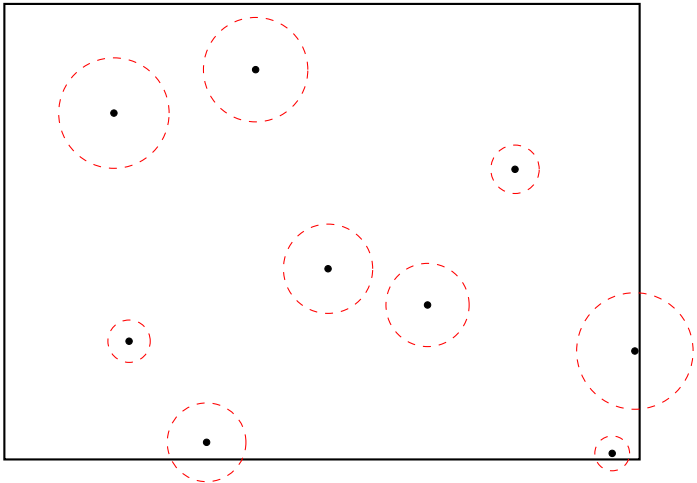


Adapted Minimum-Spacing Model

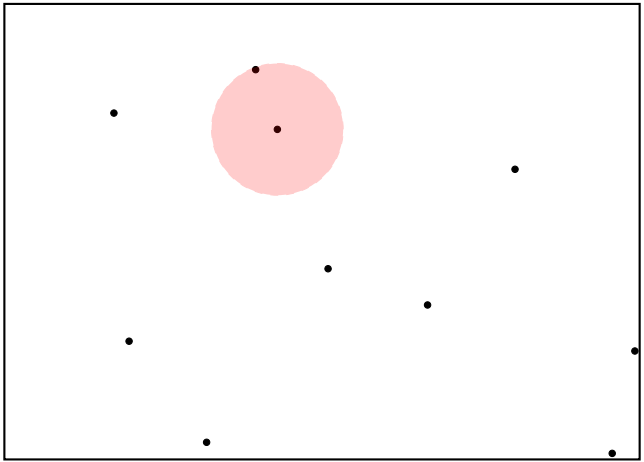
- Original model introduced for S-cones and rods of ground squirrel [Galli-Resta, 1999]
- Successfully applied to other cell types in different species [Eglen, 2012]
- Adapted to human S-, M- and L-cones by means of effective radius

Cone type	Effective radius r_e in [µm]	Minimum-spacing $d_{\min}$ in [µm]
S-cones	15.83 ± 2.82	18.00 ± 3.00
M-cones	4.93 ± 1.60	5.00 ± 1.50
L-cones	5.87 ± 1.91	8.50 ± 1.50

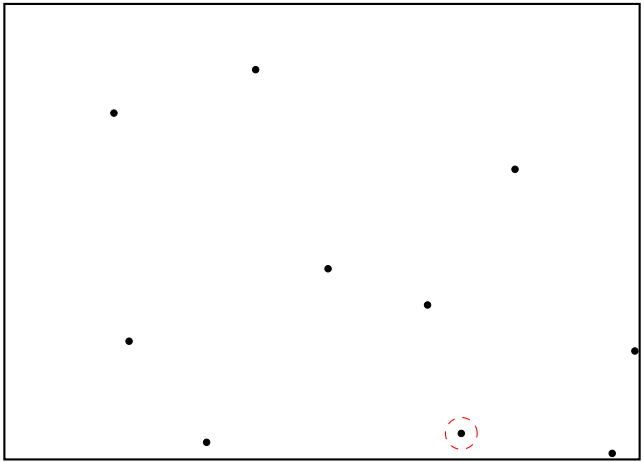
Minimum-Spacing Model [Galli-Resta, 1999]



Minimum-Spacing Model [Galli-Resta, 1999]



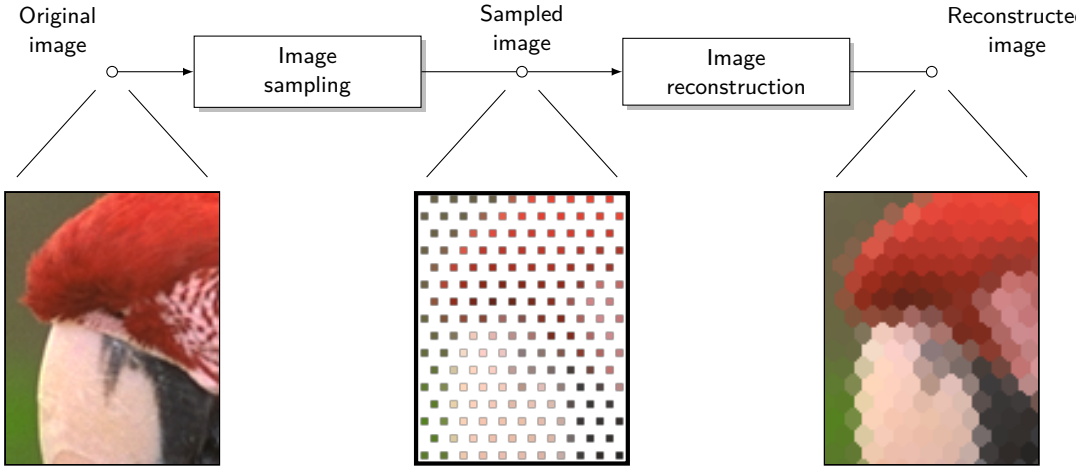
Minimum-Spacing Model [Galli-Resta, 1999]



Comparison of Available Study Results

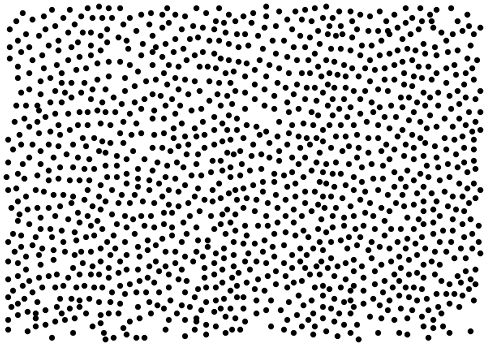
- ✓ Biological studies agree in cone density and spacing
- ✓ Measured cone mosaics agree with studies
- ✓ Modeled cone mosaics agree with measured cone mosaics

Regular and Non-regular Sampling

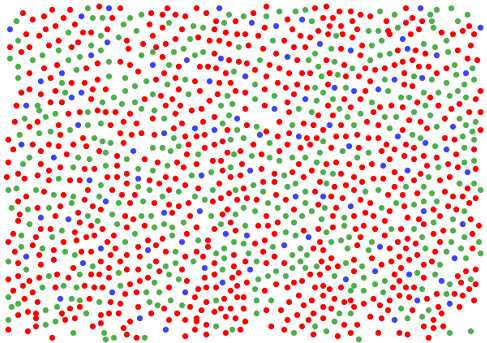


All- and SML-sampling

All-sampling



SML-sampling



All-sampling

Sampling method	Sampling point density
uniform	2.04 %
hexagonal	1.79 %
S1 at 2°	2.42 %
S1 at 3.70°	1.79 %
S2 at 3.70°	2.04 %

All-sampling

Sampling method	PSNR			SSIM		
	LI	CI	FSR	LI	CI	FSR
uniform	25.57	**26.07**	25.91	0.844	**0.850**	0.846
hexagonal	25.53	**26.03**	25.44	0.844	**0.850**	0.832
S1 at 3.70°	25.44	**25.98**	25.79	0.842	**0.848**	0.843
S2 at 3.70°	25.51	**26.04**	25.89	0.843	**0.849**	0.845
S1 at 2°	25.51	**26.02**	25.84	0.844	**0.849**	0.846

Linear Interpolation (LI), Cubic Interpolation (CI)

Frequency Selective Reconstruction (FSR)

Example All-sampling Based on S2 at 3.70°

Reference LI CI FSR

SML-sampling

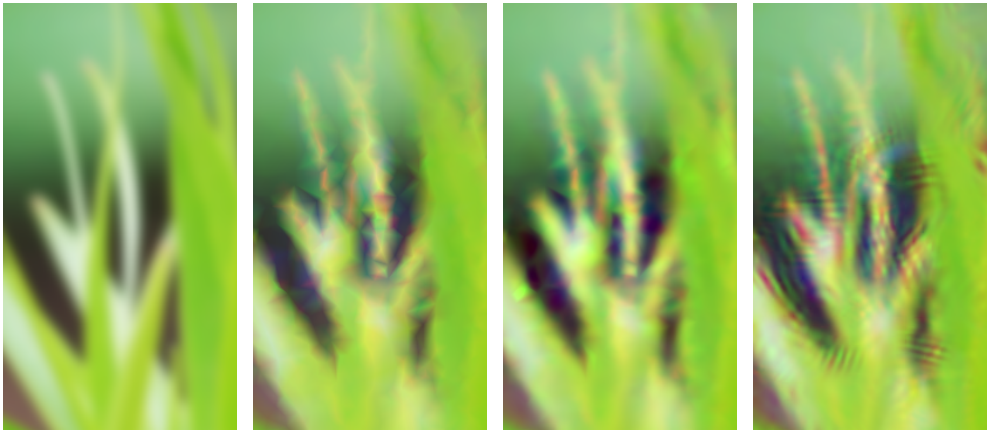
Sampling method	Sampling point density		
	R	G	B
uniform	1.56 %	0.51 %	0.15 %
S1 at 2°	1.87 %	0.40 %	0.15 %
S1 at 3.7°	1.31 %	0.34 %	0.14 %
S2 at 3.7°	1.20 %	0.68 %	0.16 %
Modeled S1 at 2°	1.87 %	0.40 %	0.15 %
Modeled S1 at 3.7°	1.32 %	0.35 %	0.14 %
Modeled S2 at 3.7°	1.20 %	0.69 %	0.16 %

SML-sampling

Sampling method	PSNR			SSIM		
	LI	CI	FSR	LI	CI	FSR
uniform	23.81	**24.45**	23.95	0.827	**0.833**	0.818
S1 at 2°	23.03	**23.50**	—	0.821	**0.822**	—
S1 at 3.70°	22.99	**23.47**	—	0.819	**0.819**	—
S2 at 3.70°	23.53	**24.10**	—	0.822	**0.824**	—
Modeled S1 at 2°	23.46	**24.01**	23.16	0.825	**0.827**	0.812
Modeled S1 at 3.70°	23.19	**23.72**	22.89	0.821	**0.823**	0.807
Modeled S2 at 3.70°	23.83	**24.48**	23.67	0.825	**0.829**	0.814

Example SML-sampling Based on Modeled S2 at 3.70°

Reference LI CI FSR



Conclusion

- ✓ Studies agree in cone density and spacing
- ✓ Measured cone mosaics agree with studies
- ✓ Modeled cone mosaics agree with measured cone mosaics

- All reconstruction methods perform similarly
- All sampling methods lead to similar results

Outlook

- Further investigation based on larger number of measured cone mosaics
- Adaption of reconstruction techniques
- Consider further properties of human visual system in model
  - Model sensitivity of cones to different wavelengths
  - Include retinal processing into model
  - Investigate spatial distribution of midget retinal ganglion cells

Bibliography I

[Adorama, 2016] Adorama

FAQ: What are the Different Camera Sensor Sizes?
https://www.adorama.com/alc/faq-what-are-the-different-camera-sensor-sizes, 2016.

[Curcio, 1990] C. A. Curcio, K. R. Sloan, R. E. Kalina, and A. E. Hendrickson

Human photoreceptor topography.
The Journal of Comparative Neurology, 1990.

[Eglen, 2012] S. J. Eglen

Cellular Spacing: Analysis and Modelling of Retinal Mosaics.
Computational Systems Neurobiology, 2012.

Bibliography II

[Galli-Resta, 1999] L. Galli-Resta, E. Novelli, Z. Kryger, G. H. Jacobs, and B. E. Reese
Modelling the mosaic organization of rod and cone photoreceptors with a minimal-spacing rule.
The European Journal of Neuroscience, 1999.

[Rodieck, 1991] R. W. Rodieck
The density recovery profile: A method for the analysis of points in the plane applicable to retinal studies
Visual Neuroscience, 1991.

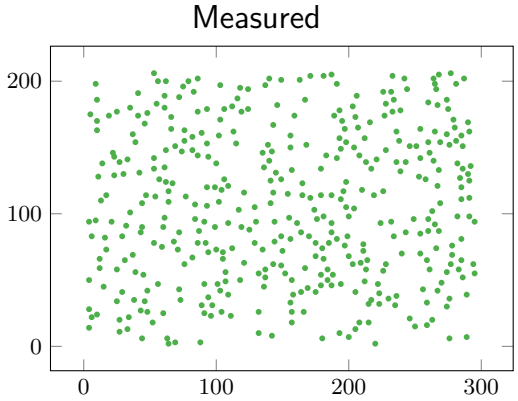
[Saey, 2015] T. H. Saey
How to rewire the eye
https://www.sciencenews.org/article/how-rewire-eye, 2015.

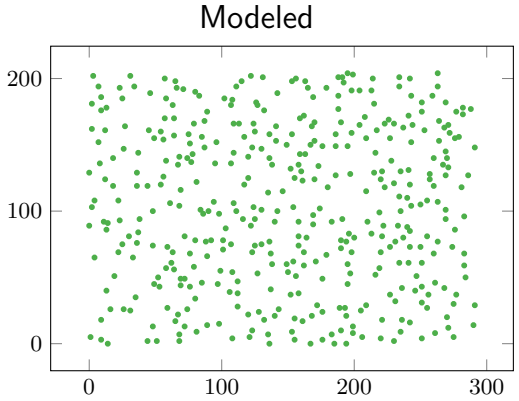
Bibliography III

[Siegel, 2012] E. Siegel
How many colors are really in a rainbow?
https://scienceblogs.com/startswithabang/2012/08/14/how-many-colors-are-really-in-a-rainbow, 2012.

[Zhang, 2019] F. Zhang, K. Kurokawa, A. Lassoued, J. A. Crowell, and D. T. Miller
Cone photoreceptor classification in the living human eye from photostimulation-induced phase dynamics.
Proceedings of the National Academy of Sciences of the United States of America, 2019.

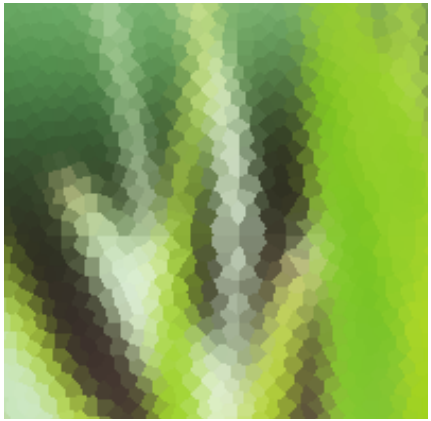
Measured and Modeled M-cone Mosaic for S2 at 3.70°



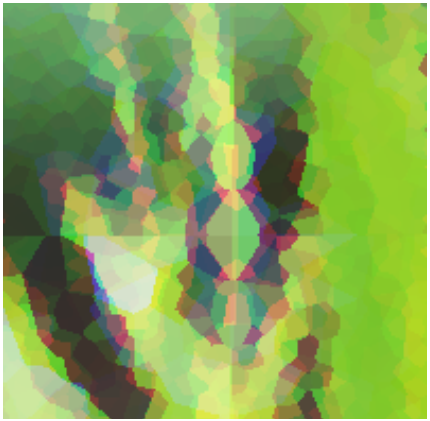


All- and SML-sampling

All-sampling



SML-sampling



Example SML-sampling Based on Measured Mosaics with CI

S1 at 3.70°

S2 at 3.70°

Example SML-sampling Based on Modeled Mosaics with CI

S1 at 3.70°

S2 at 3.70°

Investigated Studies

Study	Density	ICD	NND	FND	%-six-sided	Coordinates
[Curcio, 1990]	✓	●	●	●	●	●
[Roorda, 2001]	●	●	●	●	●	✓
[Lombardo, 2013]	✓	●	●	●	●	●
[Park, 2013]	✓	●	✓	●	✓	●
[Cooper, 2016]	✓	✓	✓	✓	✓	●
[Legras, 2018]	✓	✓	●	●	✓	●
[Wang, 2019]	✓	●	●	●	●	✓
[Zhang, 2019]	●	●	●	●	●	✓

Inter Cell Distance (ICD), Nearest Neighbor Distance (NND),Farthest Neighbor Distance (FND), Percentage of cells with six neighbors (%-six-sided)

Bibliography Appendix I

[Cooper, 2016] R. F. Cooper, M. A. Wilk, S. Tarima, and J. Carroll
Evaluating Descriptive Metrics of the Human Cone Mosaic
Investigative Ophthalmology and Visual Science, 2016.

[Legras, 2018] R. Legras, A. Gaudric, and K. Woog
Distribution of cone density, spacing and arrangement in adult healthy retinas with adaptive optics flood illumination.
Public Library of Science (PLOS One), 2018.

[Lombardo, 2013] M. Lombardo, S. Serrao, P. Ducoli, and G. Lombardo
Eccentricity dependent changes of density, spacing and packing arrangement of parafoveal cones
Ophthalmic and Physiological Optics, 2013.

Bibliography Appendix II

[Park, 2013] S. P. Park, J. K. Chung, V. Greenstein, S. H. Tsang, and S. Chang
A study of factors affecting the human cone photoreceptor density measured by adaptive optics scanning laser ophthalmoscope.
Experimental eye research, 2013.

[Roorda, 2001] A. Roorda, A. B. Metha, P. Lennie, and D. R. Williams
Packing arrangement of the three cone classes in primate retina
Vision Research, 2001.

[Wang, 2019] Y. Wang, N. Bensaid, P. Tiruveedhula, J. Ma, S. Ravikumar, and A. Roorda
Human foveal cone photoreceptor topography and its dependence on eye length.
eLife, 2019.