Visual statistics of aquatic environments from zebrafish natural habitats

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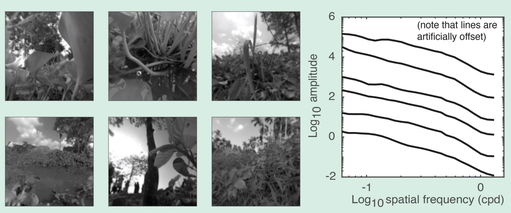
Introduction

According to the efficient coding hypothesis, animals' visual systems are adapted to exploit the regularities of natural environments in order to encode maximal sensory information with minimal metabolic cost (Attneave 1954, Barlow 1961). The visual regularities associated with natural environments can be characterized empirically through large image or video datasets. While common features have emerged in the study of these natural visual statistics (e.g., Field 1987, Dong & Atick 1995, Simoncelli & Olshausen 2001), it is also clear that different environments and contexts can place different demands on the visual system. Thus, when evaluating the efficiency of visual processing, it is best to characterize the statistics associated with the specific habitat of the animals being studied (*e.g.*, Laughlin 1981, Tkačik *et al.* 2011, Baden *et al.* 2013, Clark *et al.* 2014, Zimmermann *et al.* 2018).

Zebrafish (*Danio rerio*) are a popular model in visual neuroscience due to their amenability to advanced research tools and their diverse set of visually-guided behaviors. However, little is known about the spatiotemporal features of the habitats where zebrafish reside (Arunachalam *et al.* 2013, Zimmermann *et al.* 2018). In the present study, we aim to characterize the visual statistics of aquatic environments in Assam, India, where zebrafish are native.

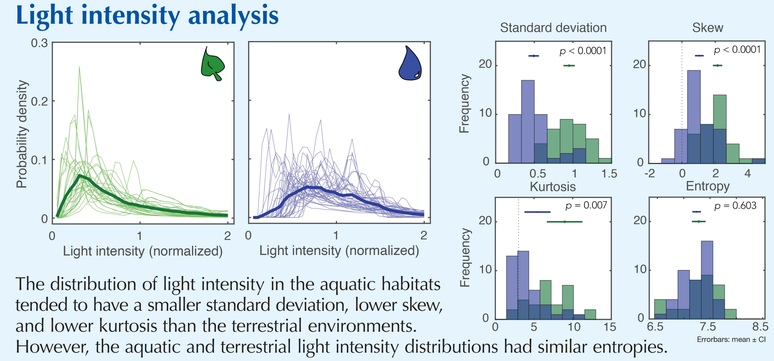


Six different terrestrial natural images (on the left) captured in Assam, India are quite variable in visual appearance.

An examination of their spatial amplitude spectra (on the right) reveals a common structure in the frequency domain (Field 1987). What structures are typical where zebrafish reside underwater?

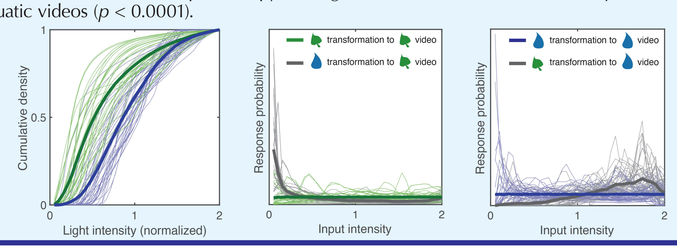
Results

Light intensity analysis

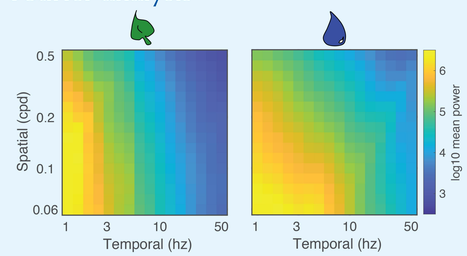


The distribution of light intensity in the aquatic habitats tended to have a smaller standard deviation, lower skew, and lower kurtosis than the terrestrial environments. However, the aquatic and terrestrial light intensity distributions had similar entropies.

We used a standard method for determining the optimal transformation to encode these intensities with maximum response entropy (simply the cumulative) (Laughlin 1981). The results suggest that optimal response non-linearities for visual neurons encoding the zebrafish habitat should be relatively steep. Applying the aquatic transformation to the terrestrial videos resulted in sub-optimal response distributions, and vice versa. The difference between optimal and sub-optimal response distributions in terms of output entropy was significant for both terrestrial videos ($p < 0.0001$) and aquatic videos ($p < 0.0001$).



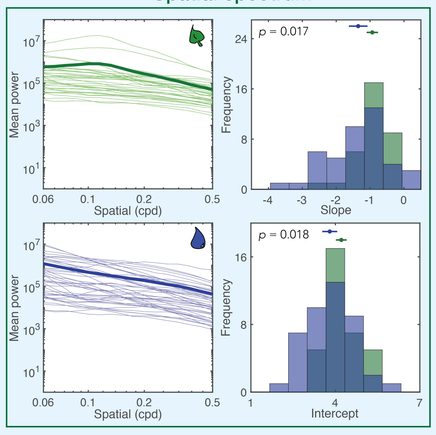
Fourier analysis



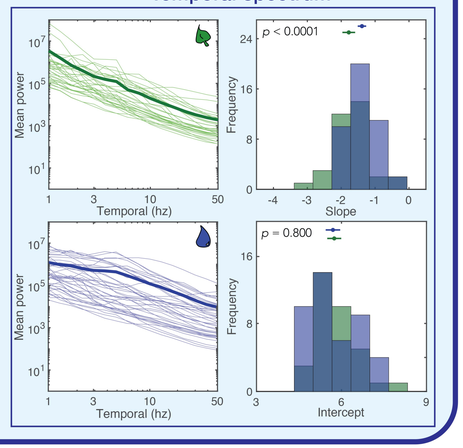
The average spatiotemporal power tended to be lower across a range of frequencies in the aquatic habitats. This is possibly related to turbidity.

We fitted the marginal spatial spectrum and temporal spectrum with a linear model, and compared the slopes and the intercepts between terrestrial and aquatic marginals. In the spatial domain, we found that the aquatic spectra had steeper slopes and lower intercepts. In the temporal domain, the slopes of the aquatic spectra were shallower, possibly related to underwater caustics (Maximov 2000).

Spatial spectrum



Temporal spectrum



Methods

Data collection

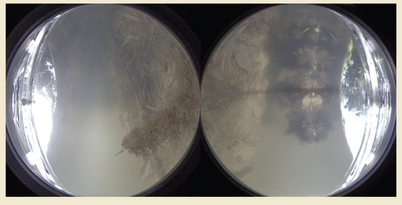
We recorded videos from a variety of zebrafish habitats in Assam, India in October 2019. Videos were captured using a novel robotic system that was comprised of a 360° high-framerate underwater camera (pictured to the right), motorized gantries (30 cm travel) for 3D translation, and a rotation motor for yaw control. The current analysis focuses on stationary videos.

Insta360 camera

Video processing pipeline

- Blur/downsample to remove compression artifacts
- ↓ Remove spatial distortion
- ↓ Linearize pixel values
- ↓ Equalize angular resolution
- ↓ Perspective projection

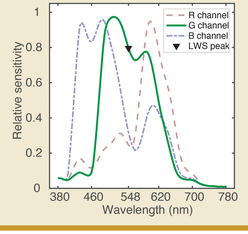
An example raw frame



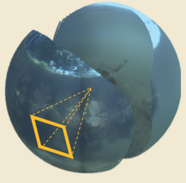
Data analysis

We created 34 video clips from terrestrial areas and 43 from aquatic areas. Each clip has 1001 frames (10 s) and a spatial span of 75°-by-75°. We analyzed the light intensity distribution and the spatiotemporal power spectrum based on the green channel of the videos, which responded well at the peak of zebrafish long-wavelength sensitivity (548nm, right). Long-wavelength signals are critical to zebrafish motion perception (Orger *et al.* 2005, Zimmermann *et al.* 2018).

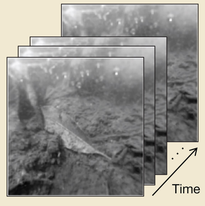
Camera spectral sensitivity



Undistorted projection on sphere



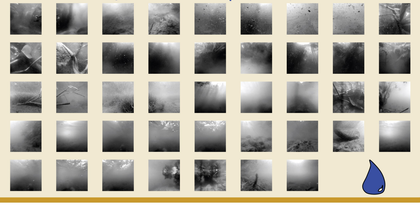
An example clip



We structure our analysis by comparing the visual appearance of aquatic videos from the zebrafish habitats to a control dataset of terrestrial videos captured in nearby environments. Some of the terrestrial clips share similar scenes but were recorded at different times. We used unpaired *t*-tests for statistical analyses.

34 terrestrial video clips from 4 sites

43 aquatic video clips from 8 sites



Summary

The aquatic environments from zebrafish natural habitats exhibit a range of visual statistics different from the terrestrial environments in the same area.

Optical and physical properties of aquatic environments may cause a reduced frequency of high contrast visual input. They may also introduce additional challenges to motion encoding, due to the prevalence of caustics and global environmental motion from water flow.

These visual statistics have likely guided the evolution of the zebrafish visual system towards efficient coding goals that differ from terrestrial animals.

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References

Arunachalam, M., Raja, M., Vijayakumar, C., Malaiammal, P., & Mayden, R. L. (2013). Natural history of zebrafish (Danio rerio) in India. Zebrafish, 10(1), 1-14.
Attneave, F. (1954). Some informational aspects of visual perception. Psychological review, 61(3), 183.
Baden, T., Schubert, T., Chang, L., Wei, T., Zaichuk, M., Wissinger, B., & Euler, T. (2013). A tale of two retinal domains: near-optimal sampling of achromatic contrasts in natural scenes through asymmetric photoreceptor distribution. Neuron, 80(5), 1206-1217.
Barlow, H. B. (1961). Possible principles underlying the transformation of sensory messages. Sensory communication, 1, 217-234.
Clark, D. A., Fitzgerald, J. E., Ales, J. M., Gohl, D. M., Silies, M. A., Norcia, A. M., & Clandinin, T. R. (2014). Flies and humans share a motion estimation strategy that exploits natural scene statistics. Nature neuroscience, 17(2), 296-303.
Dong, D. W., & Atick, J. J. (1995). Statistics of natural time-varying images. Network: Computation in Neural Systems, 6(3), 345-358.
Field, D. J. (1987). Relations between the statistics of natural images and the response properties of cortical cells. Josa a, 4(12), 2379-2394.
Laughlin, S. (1981). A simple coding procedure enhances a neuron's information capacity. Zeitschrift für Naturforschung c, 36(9-10), 910-912.
Maximov, V. V. (2000). Environmental factors which may have led to the appearance of colour vision. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 355(1401), 1239-1242.
Orger, M. B., & Baier, H. (2005). Channeling of red and green cone inputs to the zebrafish optomotor response. Visual neuroscience, 22(3), 275-281.
Simoncelli, E. P., & Olshausen, B. A. (2001). Natural image statistics and neural representation. Annual review of neuroscience, 24(1), 1193-1216.
Tkačik, G., Garrigan, P., Ratliff, C., Milčinski, G., Klein, J. M., Seyfarth, L. H., ... & Balasubramanian, V. (2011). Natural images from the birthplace of the human eye. PLoS one, 6(6).
Zimmermann, M. J., Nevala, N. E., Yoshimatsu, T., Osorio, D., Nilsson, D. E., Berens, P., & Baden, T. (2018). Zebrafish differentially process color across visual space to match natural scenes. Current Biology, 28(13).