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, Tkaczyk 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 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.

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 gannets (30 cm travel) for 3D translation, and a rotation motor for yaw control. The current analysis focuses on stationary videos.

Data analysis
We created 34 video clips from terrestrial areas and 43 from aquatic areas. Each clip has 100 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 (540nm, right). Long-wavelength signals are critical to zebrafish motion perception (Ogret et al. 2005, Zimmermann et al. 2018).

Results
Light intensity analysis
The distribution of light intensity in the aquatic habitats tended to have a slower 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 shallow. Applying the appropriate 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 of the plots across the different frequencies. Only the terrestrial domain showed a significant power-law relationship, with the slope being positively related to underwater caustics (Maxwell 2000).

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


References