ERM 2023

17 - 20 September, 2023
Tübingen, Germany

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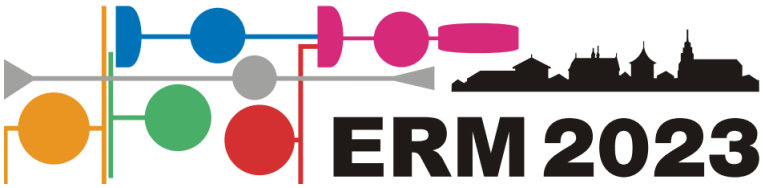
Thomas Euler
Philipp Berens
Tom Baden
Béla Völgyi

European Retina Meeting 2023

17 – 20 September, 2023 in Tübingen, Germany



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Different types of color coding ganglion cells projecting to tectum opticum in goldfish

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Each type of retinal ganglion cells (RGCs) projecting to tectum opticum (TO) in goldfish has its own color coding profile. However, the most studied types of RGCs don't have what it takes to take part in color differentiation. At the same time it is proved that fish and particularly goldfish have excellent color vision and the ability to differentiate colors. Thus, there must be several types of color-opponent units at some level in fish visual system.

We recorded electrical activity of RGCs projecting to goldfish TO from their single axon terminals. The properties of the stimuli were adjusted using the software developed for our studies. For the tests on color coding properties we calculated seven selective colors for CRT stimulation module. One color served as background color; the other six colors designated as L+, M+, S+, L-, M-, S- are designed to be discriminated only by certain type of cones. Additionally we used paired color stimuli of the same contrast to study interactions between different color channels.

Projections of color-opponent R/G cells had been first described in goldfish TO decades ago. These are units of retinal origin that we record in medial sublaminae of retinorecipient layer of TO (100 μm) along with several other RGC types. They respond to L+ stimuli and M- stimuli with short but sustained spike trains; they also respond to L- stimulation with ON-OFF short transient spike trains.

There is another group of retinal units that demonstrates color opponent properties - sustained GCs. Projections of sustained GCs form the deepest sublaminae of retinorecipient layer of TO (200 μm). There are ON and OFF types of these cells. We carried out series of experiments with selective color stimulation of 98 OFF-sustained GCs and 41 ON-sustained GCs. It turns out that OFF-type is comprised by three distinct types of cells with different color coding profiles. Type 1 and type 2 are color opponent - R/G and R/B respectively. ON-sustained cells are color-opponent R/G cells. These three types of GCs demonstrate different color interactions within center of RF and have full opponency between center and periphery of their RFs. Type 3 OFF-sustained cells usually respond to every selective color stimulus presented.

Thus, there are several ganglion cell types projecting to TO that have the ability to differentiate colors. This serves as evidence that color processing might take place in TO.

Acknowledgments: Institute for Information Transmission Problems of the Russian Academy of Sciences

Various types of color coding ganglion cells projecting to *tectum opticum* in goldfish.

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Color-opponent projections in tectum opticum of goldfish

Every type of retinal ganglion cells (RGCs) projecting to *tectum optimum* (TO) in goldfish has its own color coding profile. But only two types of RGCs show such property as color opponency both in the center and on the periphery of their receptive fields (RFs). Those are R/G GCs (8) and sustained GCs (10, 11). Sustained GCs are represented by ON and OFF types. These types of GCs differ in depth of retinorecipient layer of TO they are recorded at, and in their responses to achromatic stimulation.

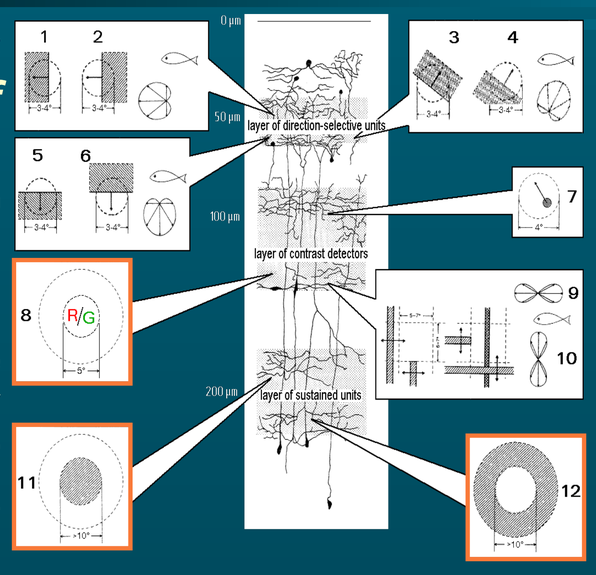

Fig. 1: Stratification of retinal activity in the tectum opticum in fish.

R/G cells

These GCs have been described in retinotectal system of goldfish decades ago. They respond to L+ and M– stimuli with sustained spike trains (Fig. 4, left section). They had also been shown to have color constancy properties in electrophysiological experiments (Fig. 4, right section). When presented with achromatic stimuli R/G cells show preference to dark stimuli, but the spike trains are shorter than those to preferred colors.

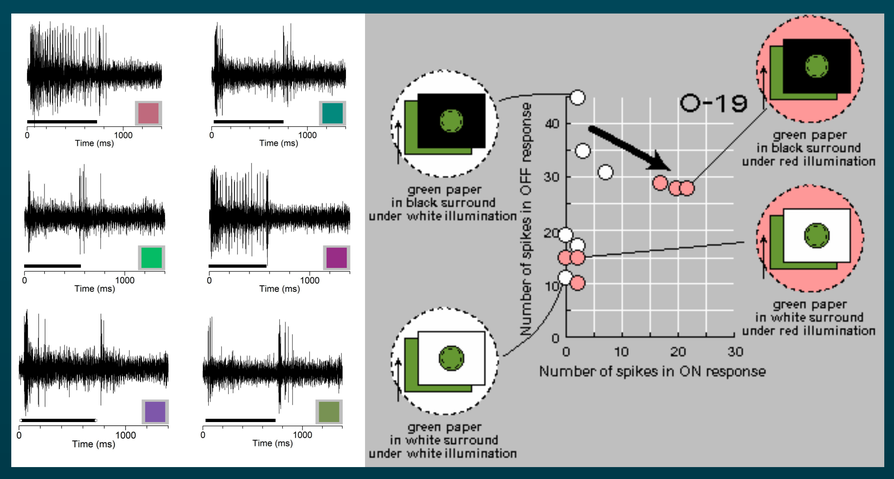

Fig.4: Color properties of R/G cells. Left section: responses to incremental (left) and decremental (right) color stimuli. Right section: color constancy properties of R/G cells (based on Maximova, 1977)

Methods

Spike activity of all GCs was recorded extracellularly from their axon terminals in the tectum opticum of *Carassius gibelio in vivo*. We recorded responses to programmable software-generated stimuli (Fig. 2).
In goldfish L, M and S cones show their maximum sensitivity at 622, 535 and 454 nm respectively. We have calculated monitor colors in order to perform selective color stimulation (Fig. 3). One of the colors served as background color (neutral gray). Six others (designated as L+, M+, S+ and S–, L–, M–) are characterized by increase or decrease (with respect to the background color) of their effective brightness for a corresponding cone type. In order to check for color interactions we have also calculated paired colors that affect two types of cones simultaneously.

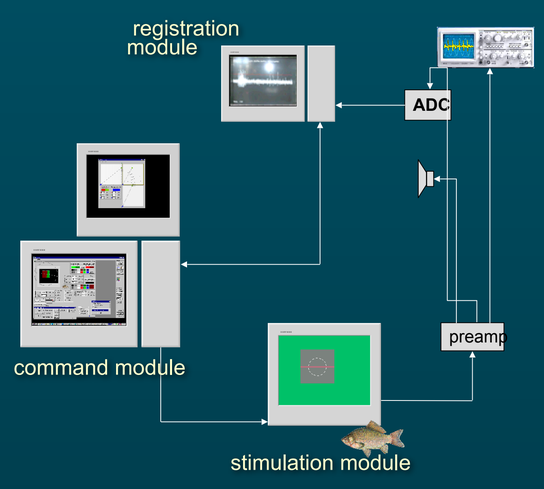

Fig. 2: Block scheme of the experimental unit.

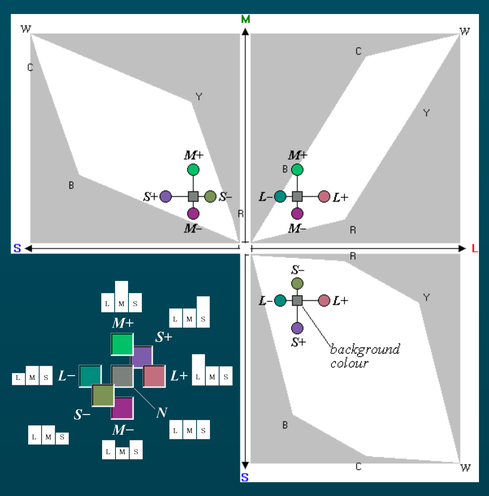

Fig. 3: Specifications of monitor colors used in stimulation procedure.

Color coding in sustained GCs

Different color stimuli evoke sustained spike response or inhibition in both ON and OFF sustained GCs. Moreover, OFF sustained GCs happen to be diverse in terms of color coding. They are represented with 3 types characterized with distinct color coding profiles (Fig. 7). Type 1 responds to L+ and M– stimuli. Type 2 responds to L– and S+ stimuli. Type 3 usually responds to all selective colors and does not have proper color-opponent properties. ON sustained GCs are uniform in terms of color coding and they respond to L+, M– and S– stimuli. When spontaneous activity to neutral background is observed, the stimulation with selective colors opposite to the preferred ones evoke inhibition of spontaneous activity. These effects show up in ON sustained GCs and type 2 of OFF sustained GCs.

Sustained GCs

This is a cluster of GCs that forms the deepest sublamina of the retinorecipient layer at the depth of approximately 200 μm. Main feature of sustained GCs is their ability to respond to static achromatic stimuli of preferred sign of contrast with a sustained spike train. Basing on contrast preference this group of cells is divided into ON sustained and OFF sustained typed of GCs (Fig. 5). RF sizes of sustained GCs are similar to other RGCs projecting to TO (5.0 ± 1.13°). Their contrast sensitivity curve in comparison to motion detectors tends to be smoother. One of the features that make sustained GCs stand out amongst retinal projections in TO is responsive peripheral part of their RFs. Flashing stimulation of periphery emits responses that are inverse to central stimulation.

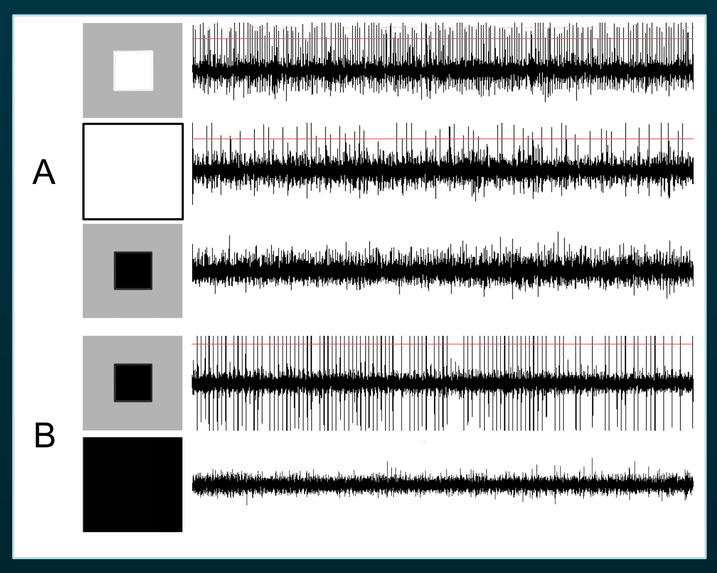

Fig. 5: Responses to achromatic stimuli of ON sustained GC (A) and OFF sustained GC (B). Configurations of presented stimuli are given on the left.

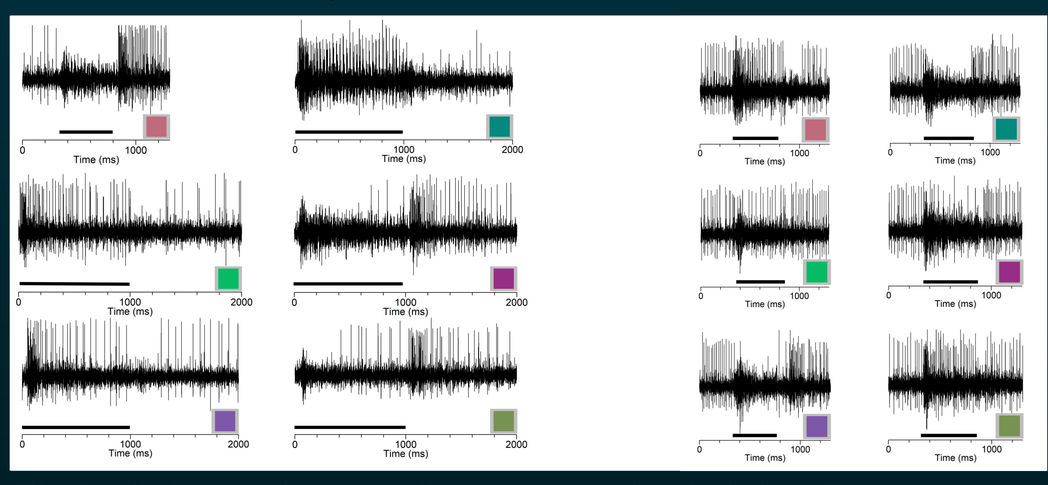

Fig.6: Color coding profiles of sustained GCs. Responses to selective color stimulation of OFF sustained GC (left section) and ON sustained GC (right section).

Color interactions in the central part of RFs

OFF sustained GCs

In type 1 of OFF sustained GCs this kind of interactions occur between L and M channels; M+ suppresses L+ component and L– suppresses M– component (Fig. 7, left section). In type 2 this concerns L and S channels; L+ suppresses S+ component and S– suppresses L– component. Type 3 does not seam to have such strong interactions in the RF and supposedly lacks color-opponent properties.

ON sustained GCs

L– component suppresses both M– and S– components. Other than that, M+ component suppresses S– component.

Periphery responses to color stimulation

Sustained GCs have responsive periphery. Cell responses to color stimulation on the periphery are just as strong as they are to stimulation of the central part of the RF. However, color coding profile of periphery is completely opposite (Fig. 9).

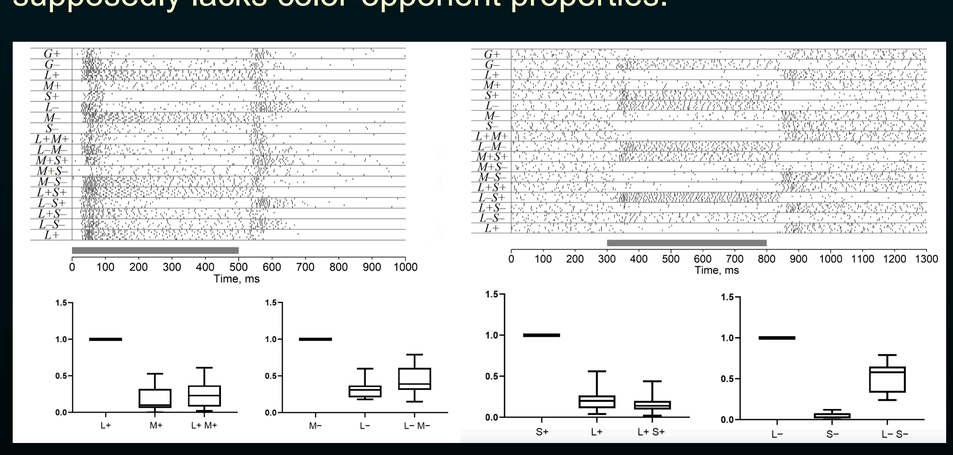

Fig. 7: Color interactions in the central part of the RFs of OFF sustained GCs. Top: examples of responses to color stimulation of type 1 (left) and type 2 (right) cells given in raster expression. Bottom: suppression effect of inhibitory components; ANOVA test used, p<0,0001.

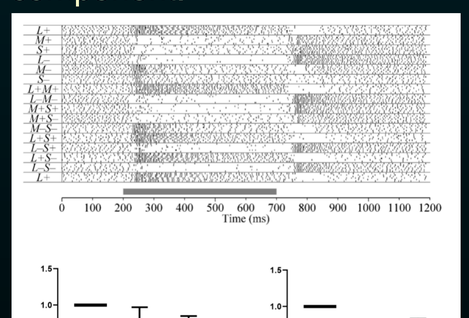

Fig. 8: Color interactions in the central part of the RFs of ON sustained GCs. Top: example of responses to color stimulation of a single cell given in raster expression. Bottom: suppression effects; ANOVA test used, p<0,0001.

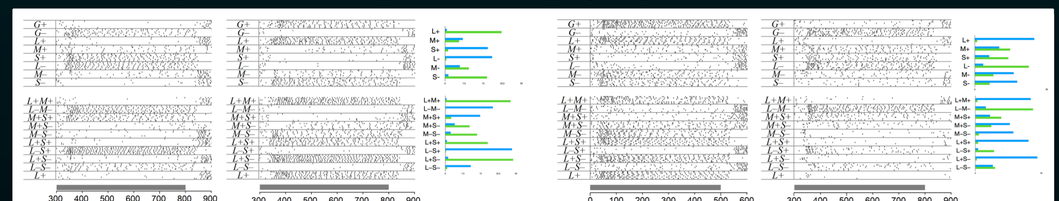

Fig. 9: Periphery responses of OFF (A) and ON (B) sustained GCs. Left sections: responses to color stimulation of the central part of the RF given in raster expression; middle sections: responses to color stimulation of the peripheral part of the RF given in raster expression; right sections: central (blue) and peripheral (green) responses to each color compared in histogram expression.

Conclusions

- ***OFF sustained GCs are comprised of 3 distinct types of cells with different color coding profiles;***
- ***OFF sustained (type 1 and type 2) and ON sustained GCs are double color opponent cells.***