

Figure 1. Flow fields generated by multiciliated cells aid olfaction.

Multiciliated cells in the larval zebrafish nose pit beat with asymmetric strokes, generating flow fields around the nose (left panel; warm colors and arrow size indicate flow strength). These flow fields push water into the nasal pit and eject them laterally. This effectively flushes odors over the sensory olfactory epithelium, enhancing odor detection and dynamic odor processing (adapted from [6] with major help from Marion Haug).

But the importance of directed, multiciliated cell-generated flows over epithelia does not stop here. Recently, multiciliated cells have been shown to play a crucial role in mammals as well [8]. Failure of these cells to generate directed fluid flows across their respective epithelia has been associated with diseases of the respiratory, reproductive

and nervous systems [9]. Hence, the study of multiciliated cells in the accessible zebrafish may very well help us to not only understand the mechanism of how these fascinating cells generate fluid flow at the cellular and molecular level, but also gain insight into the corresponding human diseases as well.

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Visual Neuroscience: Unique Neural System for Flight Stabilization in Hummingbirds

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The pretectal visual motion processing area in the hummingbird brain is unlike that in other birds: instead of emphasizing detection of horizontal movements, it codes for motion in all directions through 360°, possibly offering precise visual stability control during hovering.

The pretectum and accessory optic system (AOS) are essential visual pathways between retina and brain. They

are found in all classes of vertebrates and have a critical role in detecting the direction of image motion [1]. Signals

from the pretectum/AOS feed into the motor system to provide information relevant for maintaining eye, head and

body stability in the face of unintentional body movements. As an example of how this sensory-motor system operates, an unexpected backward body movement will generate forward image motion; the body tracks the image motion to move the body forward, thus returning it to its original position. To make this possible, the pretectum/AOS contains direction-selective neurons: these neurons respond to image motion in one direction along their preferred motion axis, and their background activity is usually inhibited by motion in the opposite direction (Figure 1A). The cells have broad directional tuning widths, meaning that similar firing rates can represent a broad range of directions, leading to ambiguity in the precise direction being indicated — more on this later. The neurons also respond optimally only when the whole visual scene moves simultaneously, as during body movements. Along with balance detectors in the inner ear (the vestibular system), pretectal/AOS neurons form an integral part of the sensory-motor circuitry that keeps humans from falling over and birds from falling out of the skies.

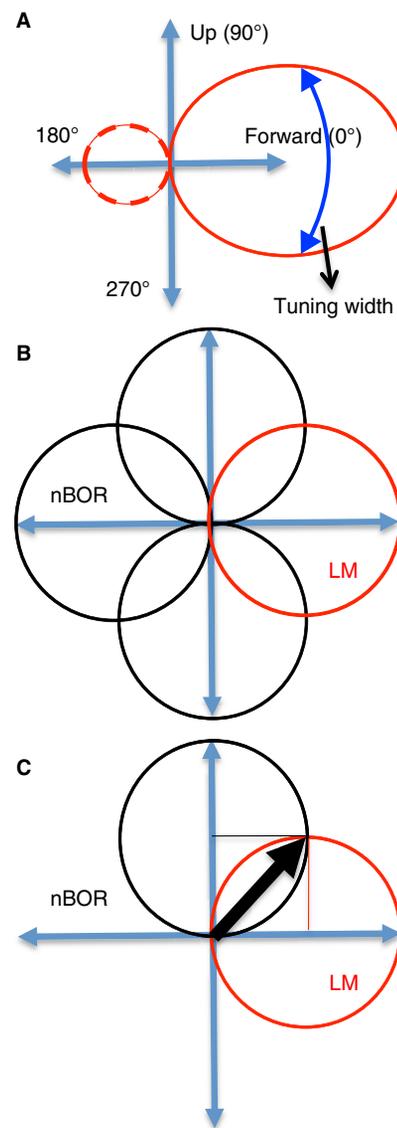
In birds, the main brain nuclei are the pretectal lentiformis mesencephalic (LM) and the nucleus of the basal optic root (nBOR). In most birds, the preferred directions of LM neurons are horizontal-forward motion in the contralateral eye (Figure 1B, red), while preferred directions for nBOR neurons are most often vertical (up or down), or horizontal backward motion in the contralateral eye (Figure 1B, black). While many consider these visual pathways a closed chapter in vision science, as they report in this issue of *Current Biology*, Gaede *et al.* [2] have uncovered a unique feature in hummingbirds — instead of preferring just horizontal-forward image motion, neurons in the hummingbird LM have preferences for all directions through 360°.

The vestibular system detects rotations about the roll, yaw and pitch axes. Roll and pitch generate vertical visual motion over the eyes and yaw generates horizontal motion. Having a pretectum/AOS that detects image motion generated by body movements around the same axes as

the vestibular apparatus makes for a robust, multi-sensory control circuit for stability control, found in species from mammals to insects [3,4]. Motion directions at non-vertical or horizontal angles can, theoretically, be calculated using the information from the orthogonally aligned detectors using trigonometry (Figure 1C). For example, if both forward-tuned LM neurons and vertical-up tuned nBOR neurons fire at half their maximum spike rate, this could be interpreted at higher neural levels as upward-forward motion at 45° (Figure 1C). But because of the broad direction tuning of the neurons and noise in the system, such solutions run the risk of imprecision.

Gaede *et al.* [2] investigated the LM of hummingbirds, which have a unique flying behavior, and compared them to the LMs in pigeons and finches, which fly using more conventional methods. Most birds utilize wing movements that generate lift partly through forward movement. Many birds are capable of hovering but this is non-optimal. Hummingbirds, on the other hand, use rapid wing beats to hover in front of flowers, which provide their food supply. It turns out that the pretectal LM in hummingbirds does not conform to the standard bird model. Instead, the neurons in the LM have several unique characteristics. It is enlarged relative to brain size compared to LMs in other birds [5], implying a special role for the nucleus. Moreover, there is a uniform distribution of preferred directions at the population level (Figure 2A) and the neurons are tuned selectively to high image speeds [2].

Let us try to make sense of the different neural machinery found in the pretectum of the hummingbird in the context of its visual environment. Most birds want to stay level relative to the visual environment, which from daily observations of bird behavior is clearly achievable using primarily vertical and horizontal tuned pretectal/AOS detectors (Figure 1C). Hummingbirds have a different problem. While staying level, they need accurately to maneuver between flowers by adjusting their wing beats from stationary-hover to moving-hover using visual cues, much like a helicopter [6,7]. On arrival at a flower,

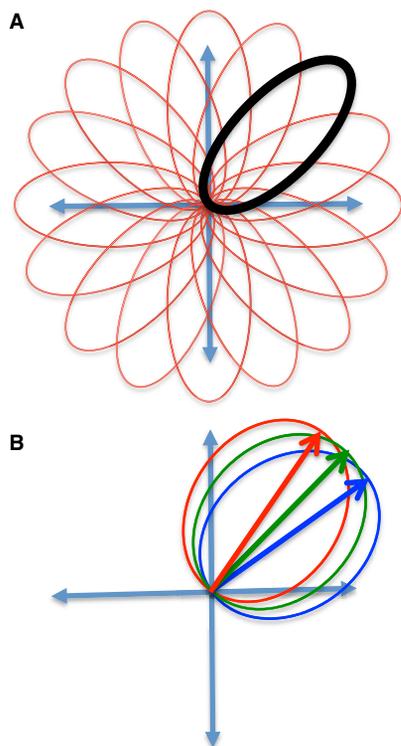


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Figure 1. Tuning functions of direction-selective neurons in the pretectum/AOS.

(A) A generic direction tuning function plotting spike rate against direction. The solid red line depicts the increased spike rate above the spontaneous rate for a range of rightward motions, while the dashed line shows the level of inhibition relative to ongoing spontaneous activity for leftward image motion. (B) Typical directional tuning functions for LM (red) and nBOR (black) in non-hovering birds. (C) The black arrow shows the actual direction of motion, which generates 50% of the maximum spike rate in both LM (vertical red line) and nBOR (horizontal black line). By comparing these spike rates, it is possible to deduce the direction of motion.

they insert their beak into the nectar reservoir and remain stationary, locked onto the visual target despite disturbances in airflow. It is only



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Figure 2. Directional tuning in the hummingbird LM.

(A) Diagrammatic illustration of the directional tuning of cells in hummingbird LM. These tuning functions are depicted as being narrow to assist in visualizing the tuning of the population. The cell shown in black signals motion up and to the right at 45°. (B) In fact, neurons in hummingbird LM have broad tuning functions and closely spaced preferred directions. Tuning functions from three cells are shown, with preferred directions 10° apart.

necessary to watch hummingbirds do this for a few minutes to realize the precision — and beauty — of their actions.

It may be the increased need for precision that leads to an increased number of directional channels in hummingbird LM. Why evolution selectively pushed pretectal LM along this route, rather than recruiting the AOS nuclei as a whole, remains an intriguing mystery. Mechanistically, the existence of many directional channels in LM may be a form of line labeling. In this scenario, each direction of unintentional body movement would be detected via a small group of direction-selective cells (Figure 2A, black tuning function). These cells would then initiate the appropriate directional motor

response to counteract deviations from the hover. Line labeling in the periphery is an established method for transferring sensory information to the brain, as in the sense of taste for example [8]. But for line labeling to work well in hummingbirds, we would predict narrow directional tuning functions, as depicted in Figure 2A. In fact, tuning functions in hummingbird LM are quite broad, with closely spaced preferred directions [2] (Figure 2B).

How could the system interpret outputs from cells with broadly tuned directional functions? Color vision mechanisms may give clues towards a mechanism. Humans have three broadly tuned color channels in the electromagnetic wavelength spectrum — short, medium and long wavelengths — with the medium and long wavelength channels not only having broad, overlapping bell-shaped absorption spectra, but also similar peak wavelengths [9]. Despite this, humans can discriminate between many hues, although only about twelve hues can be distinguished when requiring ‘absolutely identifiable differences’ [10]. Perceived color can be modeled by extracting the unique combination of response amplitudes for a given stimulus across all color channels [11]. Similarly, it is likely that unique directions are extracted from hummingbird LM by pooling across cells with similar preferred directions. The next step in working out the mechanism would be to record the responses of many LM neurons simultaneously and model the potential fidelity for directional discrimination using decoding and information theory methods at the cell population level [12,13]. These approaches have been applied to compare line labeling and pooling mechanisms in the encoding of stimulus orientation in the visual cortex [14].

Another thing that makes hummingbird LM unique is its preference for high image speeds. When flying very close to visual structures, even the slightest body movement will translate into high-speed image motion across the retina. In other birds and mammals pretectal neurons can be classed as being sensitive to either fast or slow image speeds [15–17]. In hummingbirds, only the fast cells exist. It is likely that their habit of flying close to flowers in dense vegetation has tuned the

hummingbird LM to its specific visual environment.

The pretectum and AOS have long been regarded as a highly conserved design across vertebrates. The new work by Gaede *et al.* [2] has revealed a variation in the pretectum of the hummingbird that may be a specific adaptation for hovering.

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Evolution: Selfing Takes Species Down Stebbins's Blind Alley

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Shifts from outcrossing to selfing have occurred thousands of times across the tree of life. By reducing the size of the gene pool, selfing should limit adaptive potential. A refreshing empirical experiment with snails supports this long-standing hypothesis.

Reproduction is an essential part of life, and many biologists are rightly obsessed with it. For one, we are all part of an uninterrupted stream of successful reproductive events that connect our parents to us, and perhaps ourselves to our children. While biparental sex (i.e., mating between two individuals, or outcrossing) is the rule for humans, this is not the only possibility in nature. In groups such as flowering plants and invertebrates, hermaphrodites are common and these individuals are capable of mating with themselves — a process known as ‘selfing’ (Figure 1). Upon comparing outcrossing and selfing plant species, George Ledyard Stebbins famously proposed selfing to be an evolutionary “blind alley” that constrains adaptation: “self fertilization [...] would reduce markedly the evolutionary potentialities of those lines which adopted it” [1]. The possibility of reduced adaptive potential in selfing organisms has inspired a great number of theoretical [2–5] and empirical studies on the effects of mating systems on neutral and quantitative genetic variation in nature [6–8]. However, no empirical selection experiment has yet directly put to the test a central tenet of the blind alley hypothesis — that selfing limits the rate of adaptive evolution. Now, in a

new paper in this issue of *Current Biology*, Noël *et al.* [9] test this prediction in snails.

The experimental approach was straightforward. Noël *et al.* [9] experimentally evolved snail (*Physa acuta*) populations. At the outset, replicate populations were established with one of two mating systems for 30 generations: 100% outcrossing each generation, or switching between 100% selfing and 100% outcrossing every other generation. Partial selfing causes a reduction in the effective population size and the efficacy of recombination in comparison to the fully outcrossing lines [10]. Indeed, the partially selfing lines lost 42% more of their quantitative genetic variation, which is the raw material of adaptation. After 30 generations, all of the snail populations were then subjected to artificial selection on shell shape, a trait that varies considerably within and among snail species. Individuals with the most round shells were selected under two mating regimes: 100% outcrossing or 100% selfing. This experimental design permits a decoupling of the effects of immediate selfing and a history of selfing on the rate of adaptive evolution, allowing the effects of both to be experimentally determined.

Challenging the blind alley hypothesis is a tricky business. The effects of selfing

and selection are notoriously difficult to isolate, as evidenced by Fisher’s famous line, “either inbreeding or selection, never both at the same time” [11]. This issue arises because ‘adaptive potential’ is not the same for outcrossing and partially selfing populations. In outcrossing populations, additive genetic variance is the key quantity determining the response to natural selection. With selfing, however, non-additive components of genetic variation can contribute to the response to selection [12]. It is possible to compare the



Figure 1. The flower of a primarily self-fertilizing plant species, *Mimulus laciniatus*. The evolution of selfing commonly occurs, yet its influence on adaptive potential has been difficult to test empirically. Photo: D. Grossenbacher.