RetINaBox

Lesson Plans

Version 1.0

Overview of the visual system: How do we see?

Visual processing starts in the ***retina***, a thin sheet of light-sensitive brain tissue at the back of your eye (yes, the retina is part of your brain).

Inside the retina, neurons called ***photoreceptors*** detect light and turn it into electrical-chemical signals. Through a process called *phototransduction*, light intensity changes alter the photoreceptor's membrane potential—that is, the voltage, or difference in electric potential, between the cell's inside and outside. This change in membrane potential affects how much of the neurotransmitter *glutamate* the photoreceptor releases.

These photoreceptor-mediated signals are transmitted—by helper neurons called ***bipolar cells***—to ganglion cells, which send retinal signals out of the eye and to the rest of the brain, via the ***optic nerve*** (**Figure 1**).

Within the retina, complex connectivity patterns between bipolar cells, horizontal cells, amacrine cells and ganglion cells (**Figure 1**) transform the photoreceptor-mediated signals (which themselves just signal increases or decreases in luminance) into visual feature selective responses. This means that ganglion cells respond only when specific visual features are present in the world. For instance, one ganglion might only respond when a spot of light of a particular size appears, and another ganglion cell might only respond when a visual stimulus moves from left to right across the visual field.

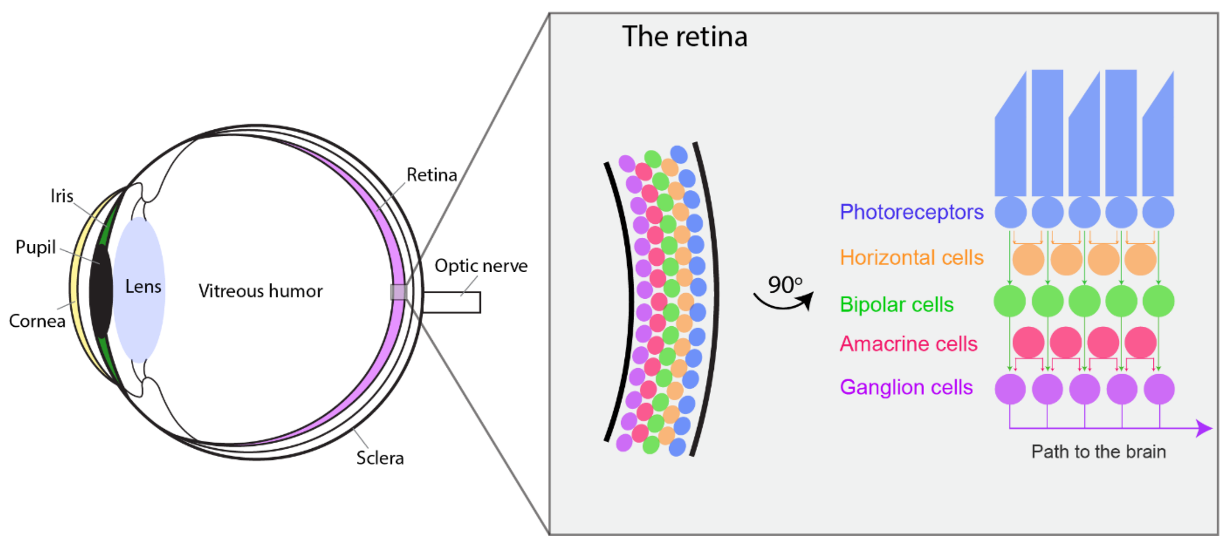


Figure 1. *A simplified diagram of the retina. Light enters the eye and is detected by photoreceptors, which send signals on to ganglion cells, via a network of additional retinal cells. Ganglion cells integrate these signals and send outputs to the rest of the brain for further interpretation.*

However, retinal anatomy is a bit more complex than outlined above. Photoreceptors (and all the other cell types pictured above) are arranged in a dense, 3D arrangement (**Figure 2**). Within a given retinal layer, cells form a 2D ***mosaic*** (**Figure 2**). For example, in the photoreceptor layer, each individual photoreceptor captures changes in luminance from a tiny portion of the visual scene, but together all the photoreceptors encode the complete image that represents your visual field.

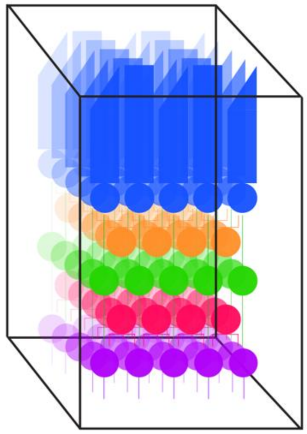


Figure 2. *Diagram of the retina illustrating the mosaic-like arrangement of cells in the retina.*

**For a more detailed overview of the retina, visit theopenbrain.org and https://webvision.med.utah.edu/.*

RetINaBox: a simplified model of the early visual system

As you've seen, the real retina is complex, with many cell types intricately connected to form a myriad of circuits. ***RetINaBox*** is a simplified model of the retina (**Figure 3**) that preserves the key principles of visual processing but provides a hands-on tool that you can use to wire, tweak, and test out visual computations. In other words, it was designed to let you discover how the retina works. RetINaBox contains a 3 x 3 array of model photoreceptors, which directly connect to two model retinal ganglion cells.

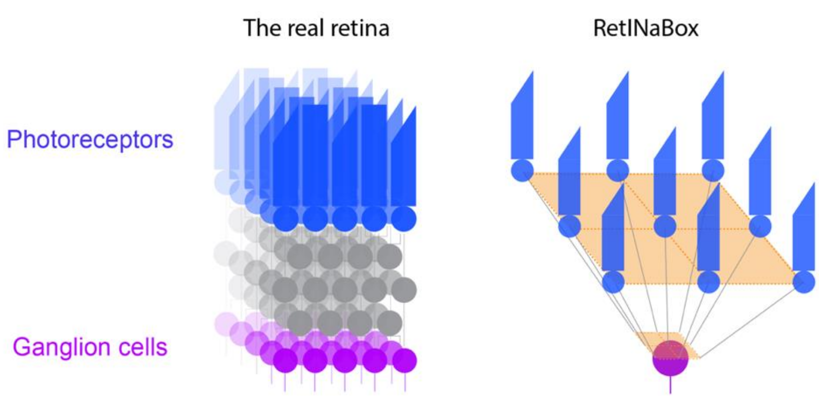


Figure 3. *Circuitry of the simplified model RetINaBox. Light is detected by photoreceptors, which synapse on—or connect to—ganglion cells. On the right, we show the connectivity from the 3 x 3 model photoreceptor array onto one of RetINaBox's two model ganglion cells.*

RetINaBox has a few key components (**Figure 4**):

- A 3 x 3 array of light-sensitive ***photodiodes***, that act as ***model photoreceptors***, that detect changes in infrared light (from RetINaBox's visual stimulus IR LEDs) and convert these visual signals into electrical signals that they then send to 2 model retinal ganglion cells.
- Two ***model retinal ganglion cells (RGCs)*** that integrate signals from the model photoreceptors

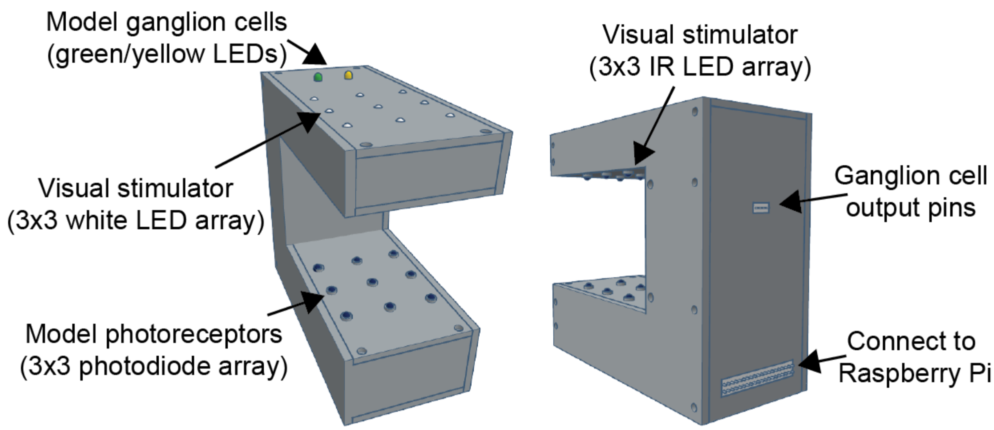


Figure 4. *Annotated diagram of RetINaBox (front view (left), rear view (right)).*

Each ganglion cell responds when it receives positive inputs from a sufficient number of photoreceptors, based on a user-defined threshold. Each photoreceptor can connect to either or both ganglion cells. **You get to decide:**

- **Polarity:** whether each photoreceptor activates (excitatory, +1) or silences (inhibitory, -1) the ganglion cell to which it is connected, or whether it remains silent
- **Time delay:** how long the photoreceptor signal takes reach the ganglion cell (this models asymmetric circuit connectivity that can be helpful for enabling motion processing)
- **Threshold:** the number of positive photoreceptor inputs that a ganglion cell needs to receive to respond. If the combined input from all the connected photoreceptors does not sum past the assigned threshold, the ganglion cell stays silent.

To help you perform experiments with RetINaBox, we have designed an easy-to-use ***Graphical User Interface (GUI)***! It has three components (**Figure 5**):

(1) **Visual Stimulus Controller** (see **Fig 5**, left panel; **Fig. 6**): controls the activation of a 3 x 3 LED array, which allows precise control of which model photoreceptors get activated. You decide which LEDs are actively sending light to their respective photoreceptors ('activated' LEDs; LED activation arises once you select an LED and then turn the Visual Stimulus Controller on). LEDs can be activated in either '***Static***' mode (stationary stimuli) or '***Motion***' mode (stimuli moving left or right at slow, medium, or fast speeds). Use the '***On/Off***' button to toggle LED activation.

(2) **Connectivity Manager** (see **Fig. 5**, middle panel): allows users to connect each model photoreceptor to one (or both) ganglion cell(s), specifying the signal **polarity** (silent, excitatory (+), or inhibitory (-)) and **delay** (none, short, medium, or long**)**.

(3) **Signal Monitor** (see **Fig. 5**, right panel): displays the input to and output from each photoreceptor, and the output of each ganglion cell (ganglion cell activation is also displayed via the green and yellow LEDs on the top of RetINaBox) .

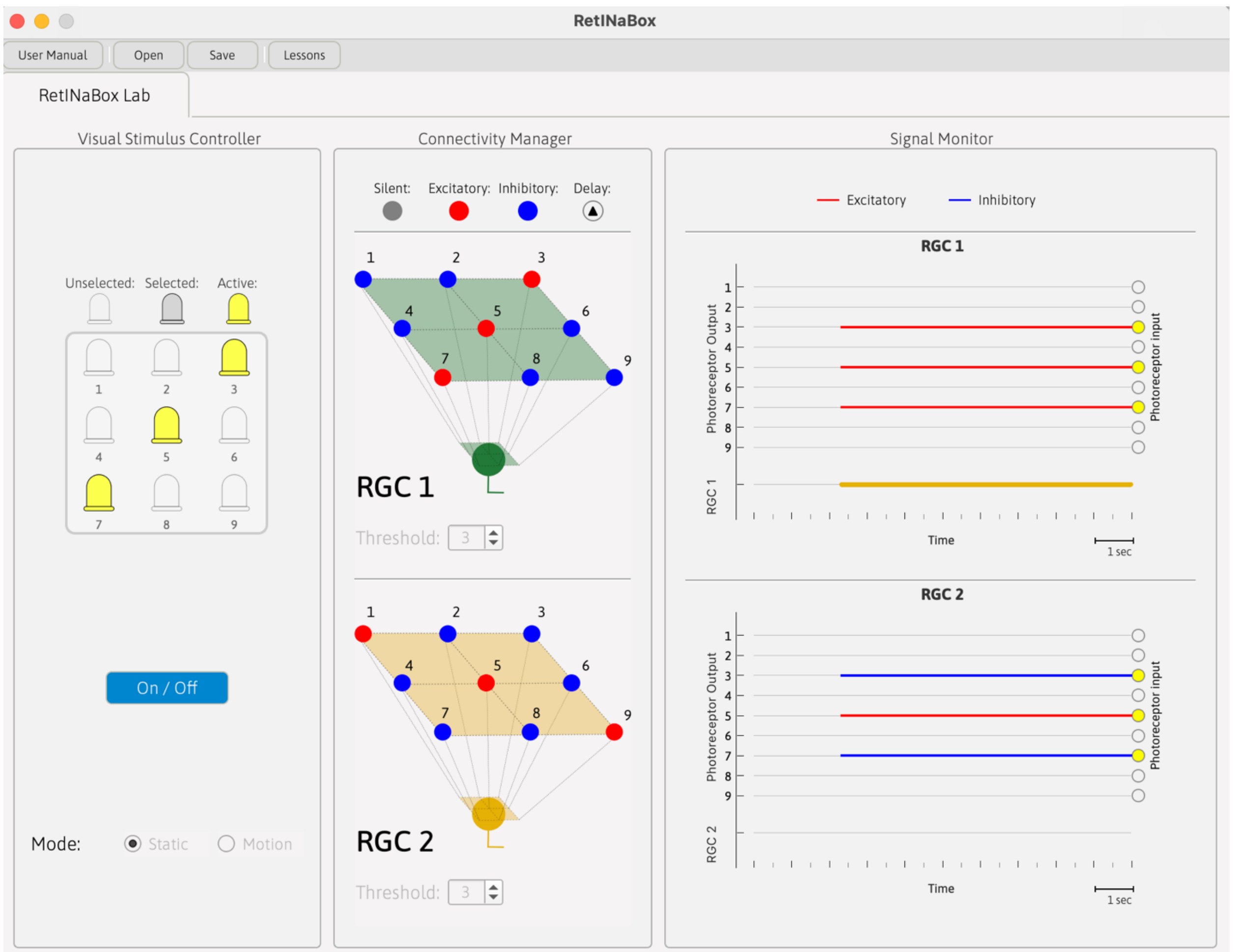


Figure 5. *RetINaBox GUI, which includes the Visual Stimulus Controller (left), Connectivity Manager (middle), and Signal Monitor (right)*

This setup is sufficient to build model ganglion cells with center-surround, orientation selective, and direction selective receptive fields—just like in the real retina!

Please refer to the* ***User Manual* *if you need further assistance with the software.*

How to test your circuits

Each lesson (outlined below) includes hands-on activities that challenge you to build retinal circuits responsive to different types of visual stimuli. For every circuit you build, you'll have two ways to test its visual selectivity:

(1) **LED activation** (see **Fig. 6**): manually activate different combinations of LEDs in the **Visual Stimulus Controller** to stimulate the model photoreceptors with different patterns of light. This is a quick way to check that your circuit behaves as expected (i.e. that your ganglion cells respond selectively to specific visual stimuli). Use the 'On/Off' button to toggle LED activation.

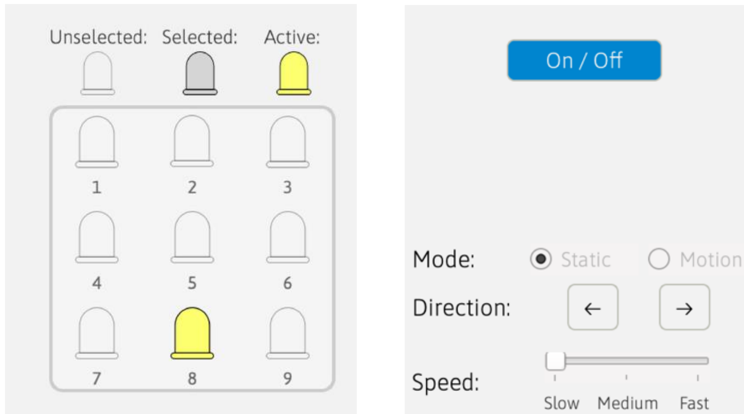


Figure 6. *Visual Stimulus Controller interface for selecting and activating LEDs in the 3 x 3 array to generate custom patterns of light stimulation.*

(2) **Manual visual stimulation with the Visual Stimulus Tool** (see **Fig. 7**): activate the entire LED array. Then, create patterns with your Visual Stimulus Tool—modeling clay on a clear plastic board. Pass this board between the LED and photoreceptor arrays to selectively block light from reaching certain photoreceptors. This is the best way to test that your visual circuit responds selectively to specific static visual inputs. Alternatively, if you're dextrous, you can just use your hands or some pieces of paper/cardboard to control the pattern of light that falls on RetINaBox's photoreceptor array. For moving stimuli, we recommend simply sweeping your hand leftward and rightward across RetINaBox's LED array.

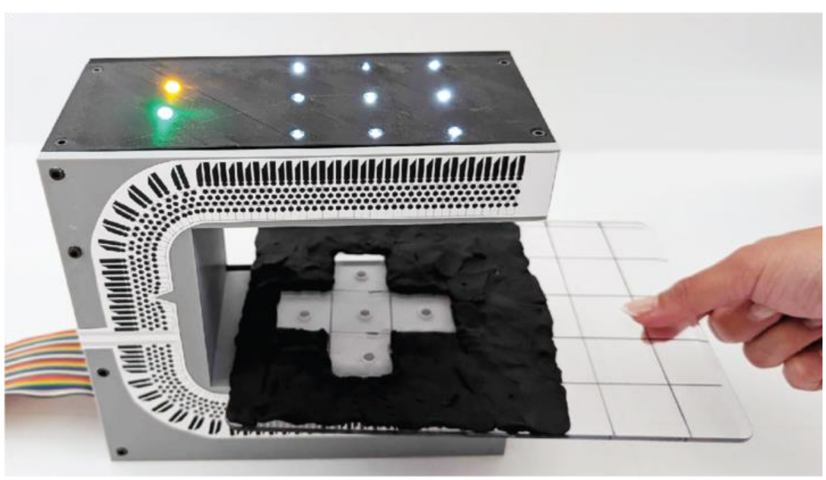


Figure 7. *Demonstration of the Visual Stimulus Tool positioned between the LED array and model photoreceptors, to selectively block light and deliver precise visual patterns to RetINaBox's photoreceptor array.*

Lesson 1: Center-Surround

How does your visual system know what to focus on in the world?

In the retina, center-surround receptive fields help visual neurons to selectively respond to local luminance contrast—that is, differences in light intensity between nearby parts of the visual field. Visual neurons with center-surround receptive fields respond when, within the small part of the visual scene that they see, one part of their receptive field is bright and another part is dark (such as dark text on a white background). Cells with center-surround receptive fields do not like homogenous visual scenes (e.g. a pure white wall), which means your visual system is optimized to detect visual stimuli that differ from plain backgrounds.

Why is this useful?

(1) Locating where something is in the world

The way our visual system detects an object's location starts at the level of individual neurons. Each visual neuron has a ***receptive field***: a specific region of the retina (and therefore, of the visual world) where changes in light intensity can alter that neuron's activity. You can think of a receptive field like a *spotlight*: each neuron's "spotlight" allows it to only see things in a specific part of the world.

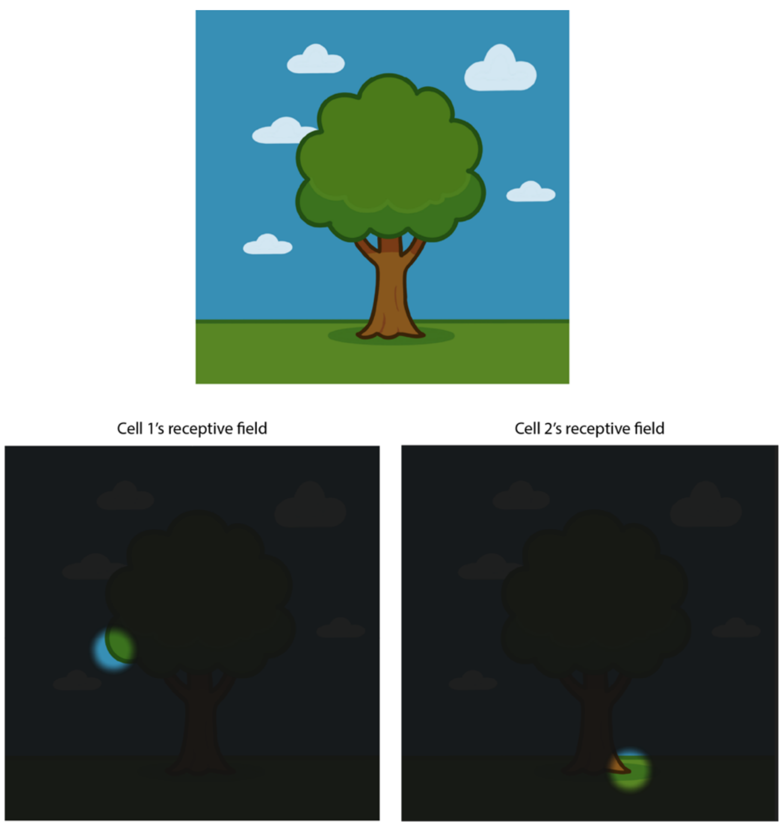


Figure 8. *Different neurons have different receptive fields.*

When a neuron is activated, it doesn't just signal that it's seeing its preferred visual feature. It also means that this feature is within that cell's receptive field. Since receptive fields from many different neurons tile the visual space in an organized way, the collection of responses from different neurons responding to a specific visual feature allows the brain to determine *where* that feature is.

Cell 1's receptive field | Cell 2's receptive field

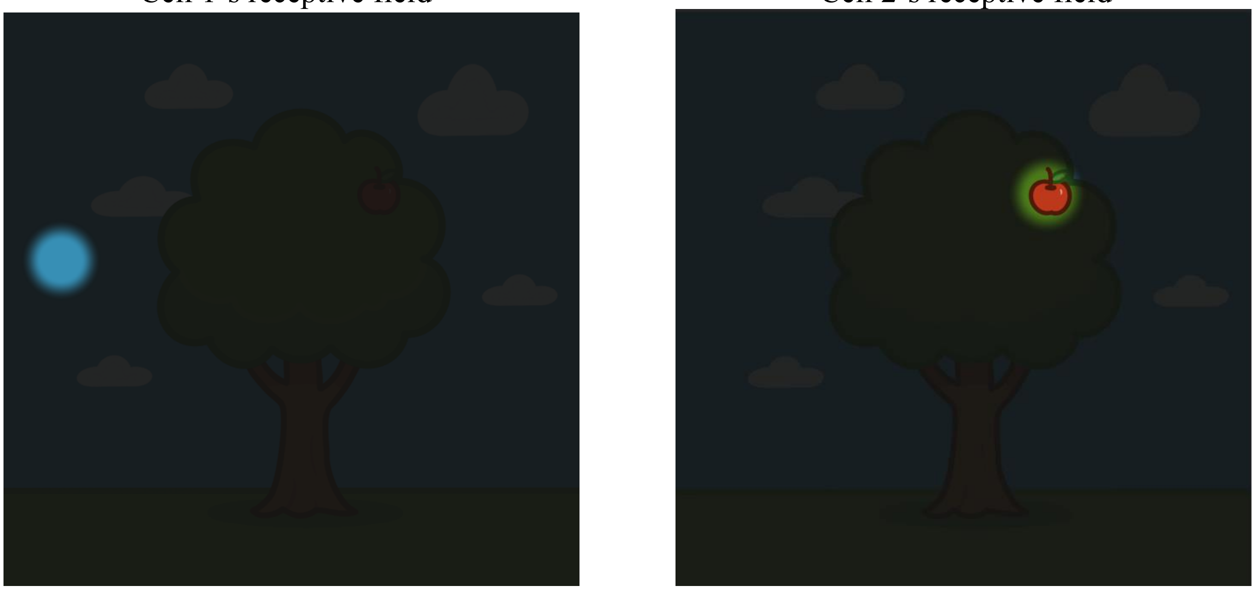


Figure 9. *Example: spotting a red apple among green leaves in a tree. Imagine two neurons, both are looking for apples in the world, but the two cells have different receptive field locations. In the example above, only the cell on the right would respond when viewing this scene.*

(2) Knowing how big something is

Aside from knowing *where* something is, we also need to know *how big* it is. For a single photoreceptor, this can be ambiguous: the feature it detects might be small and confined to its receptive field, or large enough to also activate the receptive fields of neighboring photoreceptors. The visual system addresses this ambiguity in part with center-surround receptive fields: when a visual stimulus is perfectly sized to fall directly on top of a neuron (an area termed the receptive field center), the cell maximally responds; however, if the visual stimulus is larger and extends into the region right next door to the cell (an area termed the receptive field surround), this decreases the neuron's response. This means that each neuron best responds to a visual stimulus of a particular size, matching its receptive field center, and the luminance contrast being between center and surround. Since different neurons can have receptive field centers and surrounds of different sizes, different neurons can have preferences for visual stimuli of different sizes.

Lesson 1 Objective

Build a simple circuit that mimics a center-surround retinal ganglion cell to explore how the visual system detects a focal spots of light. Then, test your circuit by activating different LEDs (in 'static' mode) to check the ganglion cell's selectivity. Finally, perform the real-world visual stimulation using the Visual Stimulus Tool to see how robust your center-surround circuit is (see *How to test your circuits section* for details).

Activity #1: build a spot detector with an ON-center/OFF-surround receptive field

Neurons with **ON-center/OFF-surround** receptive fields are *activated* (ON) by light in the very *center* of their receptive field but *inhibited* (OFF) by light in the *surrounding* area.

Use the GUI to build a circuit (RGC1) with an ON-center/OFF-surround ganglion cell that responds only when the center model photoreceptor of the 3 x 3 array is activated by light**,** but not when any of the surrounding model photoreceptors are also activated, and not when a small spot is located above any other model photoreceptor**.**

Activity #2: build a second spot detector with a different receptive field location

Your next task is to build a ganglion cell (RGC2) with the same size preference (as in Activity #1), but whose receptive field is in a **different position** on the photoreceptor array. By moving around the Visual Stimulus Tool with a small spot, you should now be able to activate each RGC, but only one at a time, based on the stimulus position.

Activity #3: build two spot detectors with preferences for spots of different sizes

Your next task is to generate **two different** ganglion cells (RGC1 and RGC2) with the same receptive field location (center) but tuned to spots of **different sizes.** One ganglion cell should detect a small spot of light, while the other should detect a **larger** spot of light. If you make two spots of different sizes with your Visual Stimulus Tool, you should only be able to only activate RGC1 with the small spot, and only active RGC2 with the larger spot.

Challenge: Codebreaking with center surround receptive fields

Now that you've learned how to make ganglion cells that selectively respond to spots of specific sizes in specific locations, we challenge you to apply what you've learned about center-surround receptive fields to **decode a hidden message**.

You will be given a series of visual stimuli; each represented as a 3 × 3 grid of photoreceptors. Some photoreceptors are activated (yellow), while others are not activated (black). Each stimulus corresponds to **one letter** of the secret message.

You will also be provided with a **cipher**, which will help you decode the message. The cipher will tell you the visual feature preferences for RetINaBox's two ganglion cells, RGC1 and RGC2. The cipher will also provide you with a way to decode the activity of RetINaBox ganglion cell activity into four letters (0 means a ganglion cell is inactive; 1 means a ganglion cell is active).

Your task:

1. From the Menu tab in the GUI, navigate to ‘Code Breaker’ (Lessons > Lesson 1 > Code Breaker).
2. In the Connectivity Manager, wire RetINaBox so that the two ganglion cells respond to the indicated visual stimuli. One important note – *make sure that it is possible for both ganglion cells to be activated simultaneously by a single visual stimulus*!
3. Use the Visual Stimulus tool to present the visual stimuli from the code to RetINaBox and monitor the responses of the ganglion cells.
4. For each visual stimulus, use the cipher to translate the RGC1/RGC2 output into a letter.
5. Repeat for each stimulus and piece together the full secret message.

See the example below (**Figure 10**):

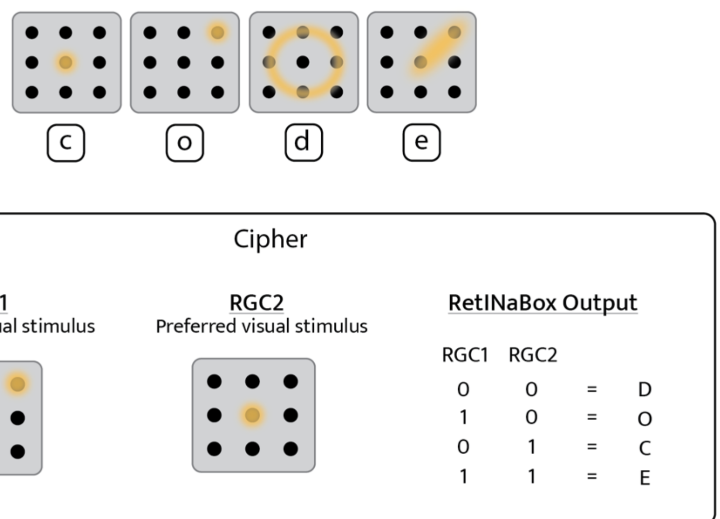


Figure 10 – Example of the code breaking game.

Challenge #1 of the code breaking activity

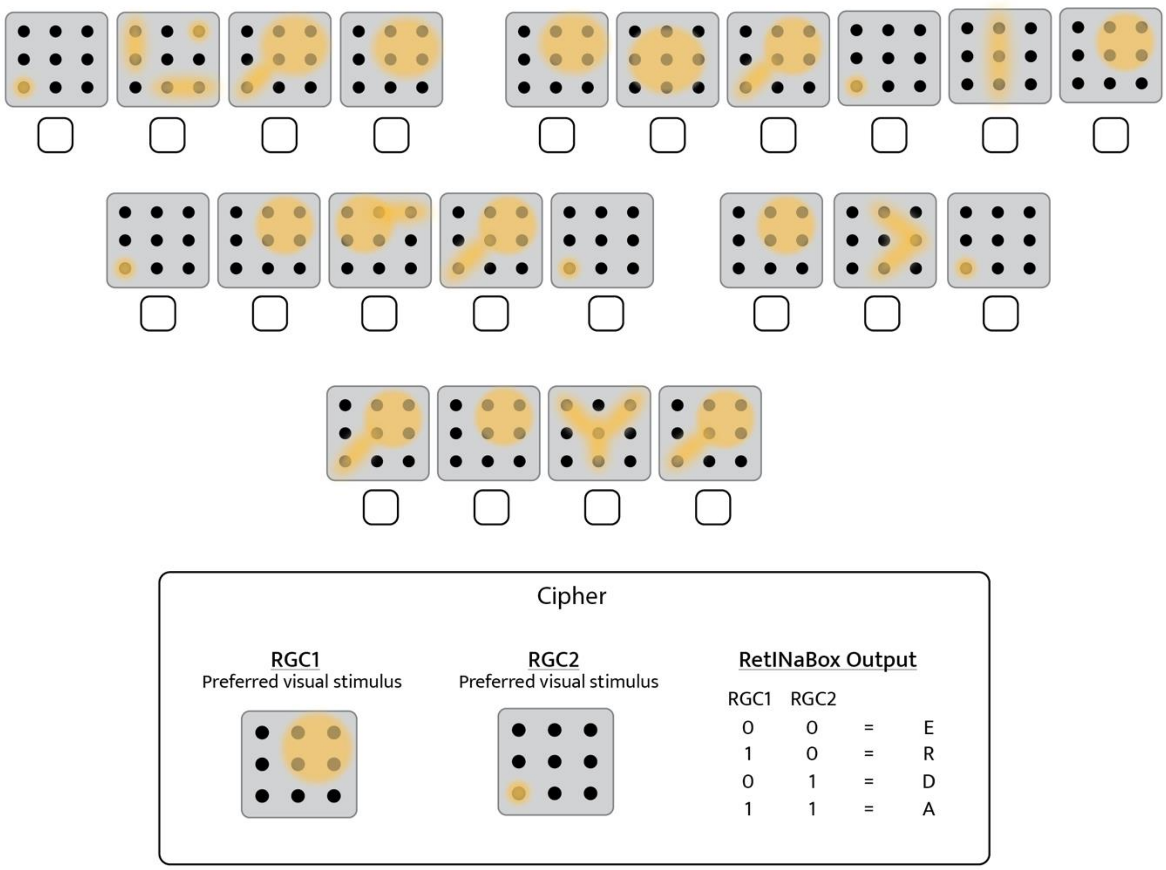


Figure 11 – Challenge 1 for the code breaking game.

**See the Lesson Plan's Appendix for the solution to this and additional codebreaking challenges.*

Lesson 2: Orientation selectivity

How do we recognize objects in the world?

As we saw in Lesson 1, our visual system is particularly sensitive to local luminance contrast. This means our visual system is great at detecting lines and edges in the visual world. However, instead of simply processing the visual world via a set of pixel detectors with center surround receptive fields, our visual system also has neurons that combine receptive fields from multiple neurons with spatially adjacent receptive field centers. This can generate visual neurons who, instead of simply being selective to luminance contrast in one tiny part of the visual scene, are selective to extended edges or lines of specific orientations within their receptive fields (see **Fig. 12**)—something termed orientation selectivity. In this lesson, you'll explore how ganglion cells in the retina can become selective to lines of specific orientations and how you can use these feature detectors to build a shape detector.

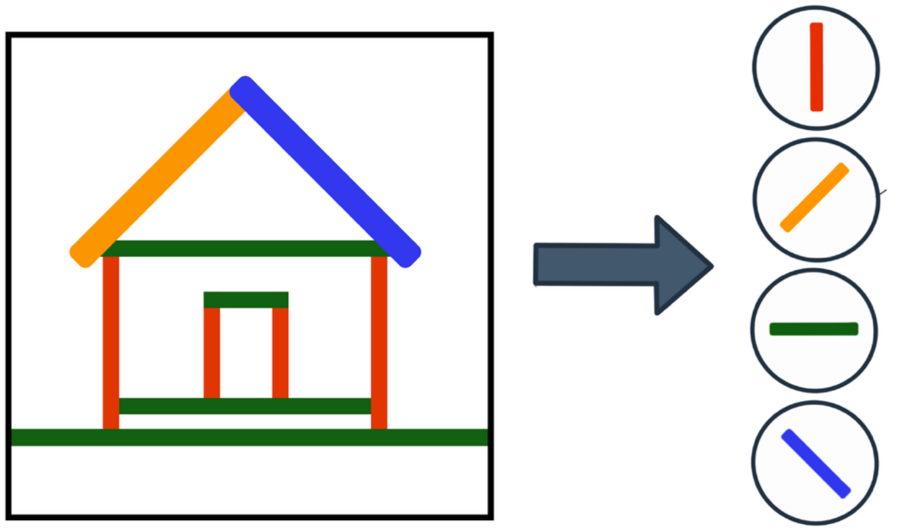


Figure 12. *Example: a house might seem like a single, familiar object - but your brain parses it by deconstructing it into many lines and edges of different angles.*

Objective

Build and test two retinal ganglion cells to model orientation selective retinal ganglion cells and use the combined tuning of these two cells to generate a shape detector. First, test your circuits by activating different combinations of LEDs (in the GUI's 'static'mode). Then, perform the real-world visual stimulation using the Visual Stimulus Tool by making a shape that is the combination of the two orientated lines that stimulate RGC1 and RGC2.

Activity #1: build a ganglion cell that detects a vertical line

Configure a circuit for RGC1 such that it only responds to a thin *vertical* line located in a specific part of the photoreceptor array. The ganglion cell should not respond to a spot of light, nor should it respond to a line of the same length of any other orientation/thickness or centered in a different part of the photoreceptor array.

Activity #2: build a second ganglion cell that detects a diagonal line

Build a circuit for RGC2 that responds to a line of the same thickness as Activity #1 but only when the line is in a diagonal orientation. This second ganglion cell should not respond to a line of any other orientation or thickness, nor to a line of the same orientation centered on a different part of the photoreceptor array.

Activity #3: build two ganglion cells that detect vertical lines of different thicknesses

Configure RGC1 and RGC2 such that both cells respond to vertical lines, but with one selectively responding to a thin line and the other selectively responding to a thick line.

Challenge: build a shape detector with orientation selective receptive fields

Your task is to combine the outputs of two orientation selective ganglion cells to detect a specific shape: the shape arising from the combination of lines that activate ganglion cell 1 and ganglion cell 2. For example, you can build a detector for an X, T, L, or +.

To make this more exciting, you'll first have to build a buzzer that sounds only when the target shape is present—meaning that the buzzer will only buzz when both ganglion cells are activated. To build the buzzer circuit, please consult the RetINaBox User Manual on pages 14-15. Once you have built the buzzer circuit, connect the outputs of the two ganglion cells (the 3.3V digital out pins on the back of RetINaBox) and one of the grounds, to the buzzer circuit (see **Fig. 13**). If you have connected the buzzer circuit correctly, it will only sound when you present your target shape. This is similar to how many neuroscientists perform their experiments—for instance, David Hubel and Torsten Wiesel, who discovered orientation selective tuning in the visual cortex of cats, often plugged in their electrophysiological recording signal into a speaker, and listened to the neurons responding as they presented visual stimuli.

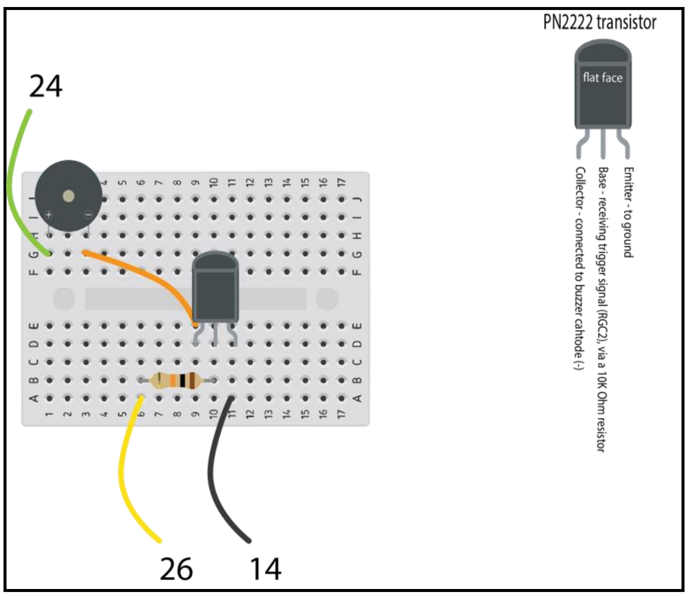


Figure 13. *Circuit wiring of the buzzer. Please See page 14-15 of RetINaBox User Manual for detailed instructions.*

Lesson 3: Direction Selectivity

So far, we've seen that some visual neurons are tuned to size and location of a visual stimulus (Lesson 1) or to the orientation of a line in the visual world (Lesson 2). It turns out that some visual neurons are even tuned to the **direction of motion** - they respond best when something moves in a particular direction within the visual field.

Why is this important? Direction selective responses help our brain know if something is approaching us or moving away from us (see **Fig. 14**). It can even help us differentiate movement in the visual world that we generate (by moving our bodies/heads/eyes) from motion that is external to us (like a bird flying in the sky).

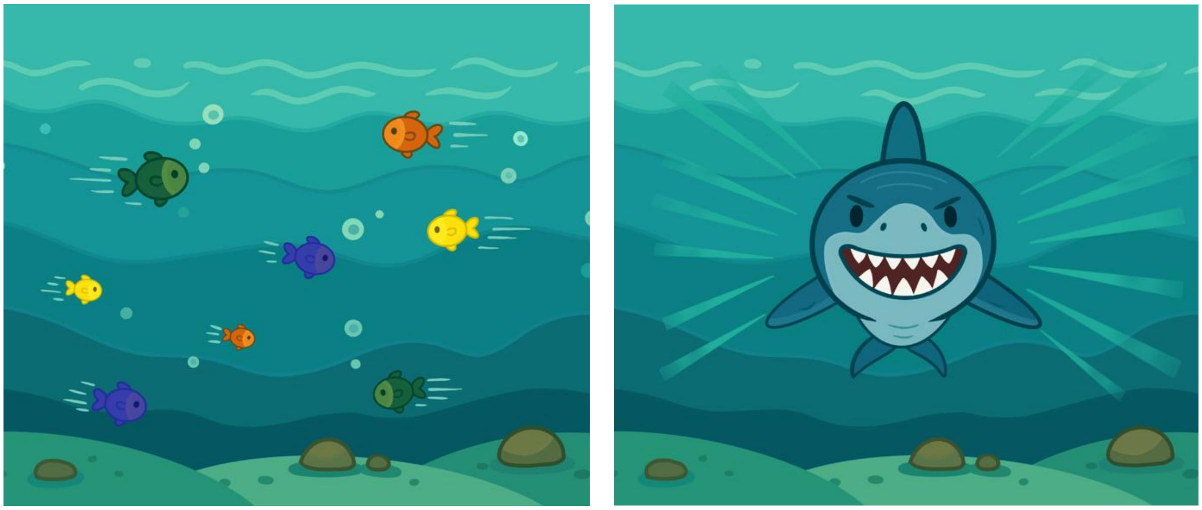


Figure 14. *Example: detecting motion in the visual world can be important for many tasks. Animals, like fish in the example here, rely on this ability to distinguish potential prey and other fish (e.g., left; small fish swimming in random directions) from predators (right; large looming shark quickly approaching).*

To generate preferences for stimuli moving in specific directions, our visual system takes advantage of the fact that a moving stimulus will activate spatially-offset photoreceptors that connect to a single downstream visual neuron in temporal sequence along the trajectory of movement—that is, photoreceptors on the leading edge of the moving stimulus get activated first, while photoreceptors on the trailing edge of the moving stimulus get activated last. This means that for a ganglion cell responding to a moving stimulus, there is a time delay between when it receives signals from photoreceptors on leading versus trailing edges of its receptive field (see **Fig. 15**).

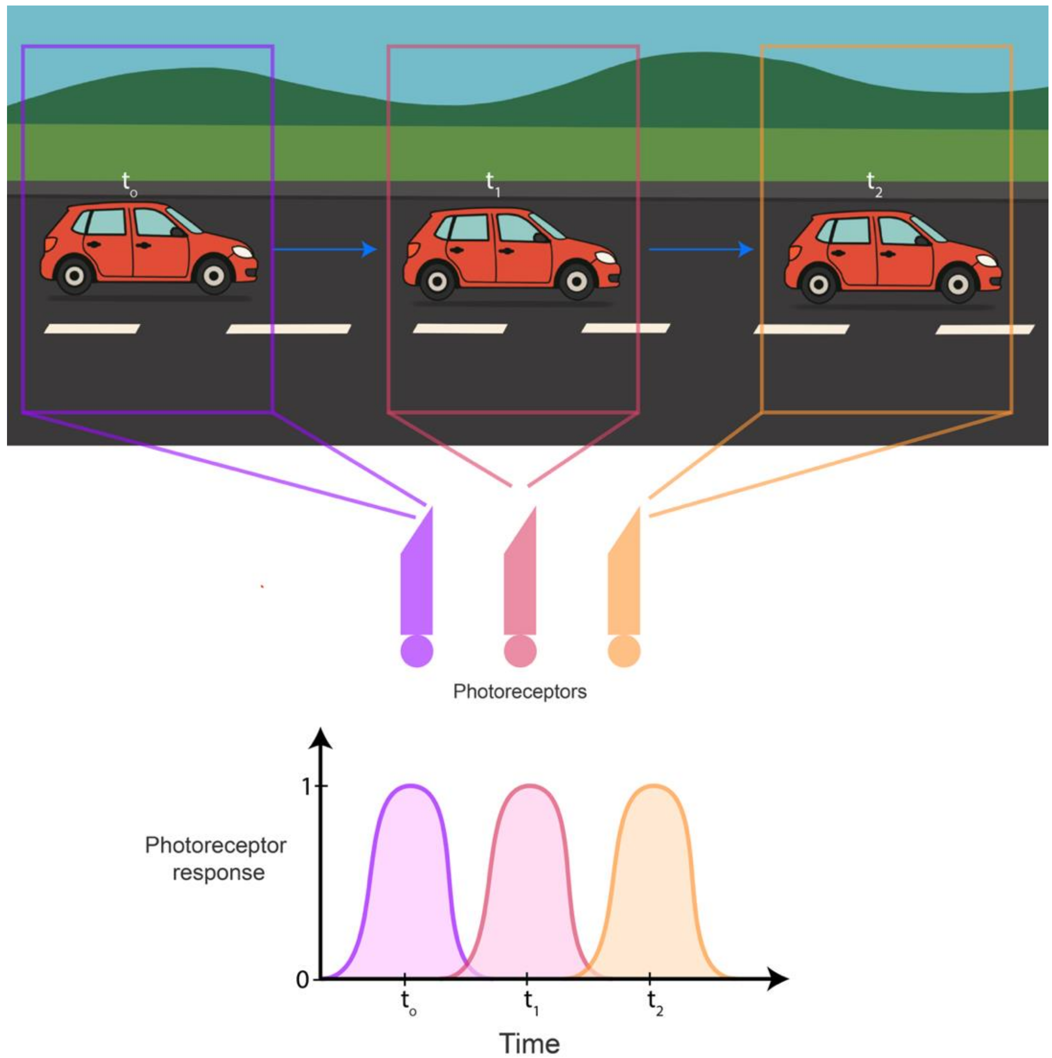


Figure 15. *As an object moves across the visual field, different photoreceptors with spatially offset receptive fields are activated in sequence, in the order that they 'see' the object. Photoreceptors at the leading edge of the motion (left) respond first, followed by those in the middle, and finally the trailing edge (right). This sequential activation produces time-delayed signals that the visual system can use to detect the direction of motion.*

Objective: build a circuit that mimics a direction selective retinal ganglion cell to understand how the visual system detects motion. First, test your circuit by activating different combinations of LEDs (use the GUI's 'Motion' mode, and select a speed and direction of motion). Then, sweep your hand across RetINaBox's field of view.

The key to direction selectivity lies in asymmetric anatomical connections that differentially process visual stimuli moving in one direction vs. the other. In RetINaBox, these asymmetric differences can be implemented with **time delays** that can be asymmetrically added in the Connectivity Manager along the right-left axis of the 3 x 3 photoreceptor array. These delays ensure that inputs to an RGC only summate (and the ganglion cell fires) when a stimulus moves in the RGC's preferred direction.

Note

- *In this section, waving your hand back and forth between the LEDs and photoreceptors to test your circuit's functionality. *We don't recommend using the Visual Stimulus Tool to test moving stimuli, due to edge artifacts that can drive spurious responses when the outer boundaries of the Visual Stimulus Tool enter and exit RetINaBox's visual field*
- *Depending on the time delays you've assigned to each photoreceptor, you may need to test different stimulus speeds (i.e. move your hand at different speeds) to observe the ganglion cell firing specifically to a single direction of movement.*

Activity #1: build a leftward motion direction selective ganglion cell ←

Build a circuit where RGC1 responds to a vertical line moving leftwards. Test your circuit by moving your hand across your array in both left and right directions.

Activity #2: build a rightward motion direction selective ganglion cell →

Next, build a second circuit where RGC2 responds to a vertical line moving rightwards. Test your circuit by moving your hand across your array in both right and left directions.

Activity #3: build a slow vs. fast motion preferring direction selective ganglion cell →

Build a circuit where RGC1 responds to a vertical line slowly moving rightwards, while RGC2 responds to a vertical line moving in the same direction, but more quickly. Test your circuit by moving your hand rightwards across your array at various speeds. **Tip – to generate RGCs with preferences for different speeds, think about what changing the time delay will accomplish.*

Challenge: Block Breaking with direction selective circuits

Block Breaker is an arcade game where players control a paddle using leftward and rightward motion to bounce a ball to break several rows of blocks. The goal is to clear all the blocks without letting the ball drop. Your task is to configure two ganglion cells with opposite direction selectivity (i.e. make two robust direction selective ganglion cells) and use them as the input controls for the game inside the RetINaBox GUI.

- **Step 1:** In the Connectivity Manager, configure both ganglion cell circuits so that RGC1 is selective *only* for leftward motion and RGC2 is selective *only* for rightward motion.

- **Step 2:** Load the game. From the Menu tab in the GUI, navigate to 'Block Breaker' (Lessons > Lesson 3 > Block Breaker).

- **Step 3:** You're now ready to play (see **Fig. 16**)! The block breaker paddle is controlled by you sweeping a visual stimulus (your hand) leftward and rightward across RetINaBox's field of view.

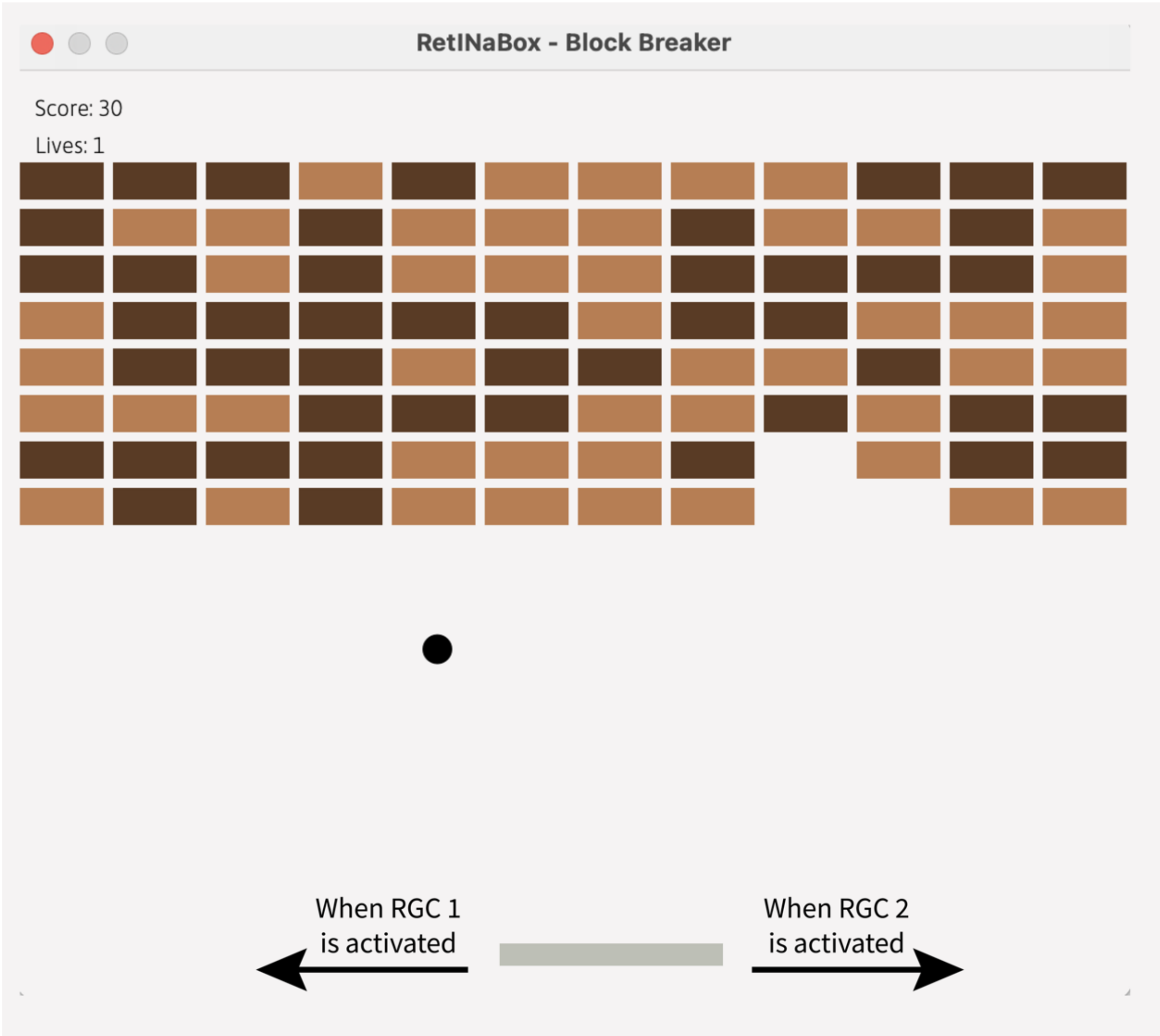


Figure 16. *Block Breaker in the RetINaBox GUI. GC1 activation should move the paddle left, while GC2 activation should move the paddle right.*

Lesson 4: Discovery Mode

Welcome to Discovery Mode! You've made it this far, which means that you're ready to perform some real experiments! In this section you'll get a taste of what it it's like to be a visual neuroscientist!

So far, you've explored center-surround, orientation selective, and direction selective receptive fields—all circuits that have already been well characterized by vision scientists. But the quest to understand what neurons "like to see" is far from over. Even today, neuroscientists are still working to discover which kinds of stimuli best activate different visual neurons in various parts of the brain. *Now it's your turn discover which visual stimuli best activate some newly discovered visual neurons and then discover what circuit connectivity properties underlie such feature selectivity.*

In Discovery Mode (see **Fig. 17**), there are three levels of difficulty (Easy, Medium, Hard), each with their own set of challenges. To complete each challenge, you'll need to discover (i.e. correctly submit an answer) the mystery ganglion cell's target visual stimulus (the visual response that drives that ganglion cell) and the circuit connectivity (the settings in the Connectivity Manager) that underlie this feature selective response. For each challenge, you'll start with 100 points, but incorrect answers cost you 5 points. Your goal is to complete each challenge with the highest score possible.

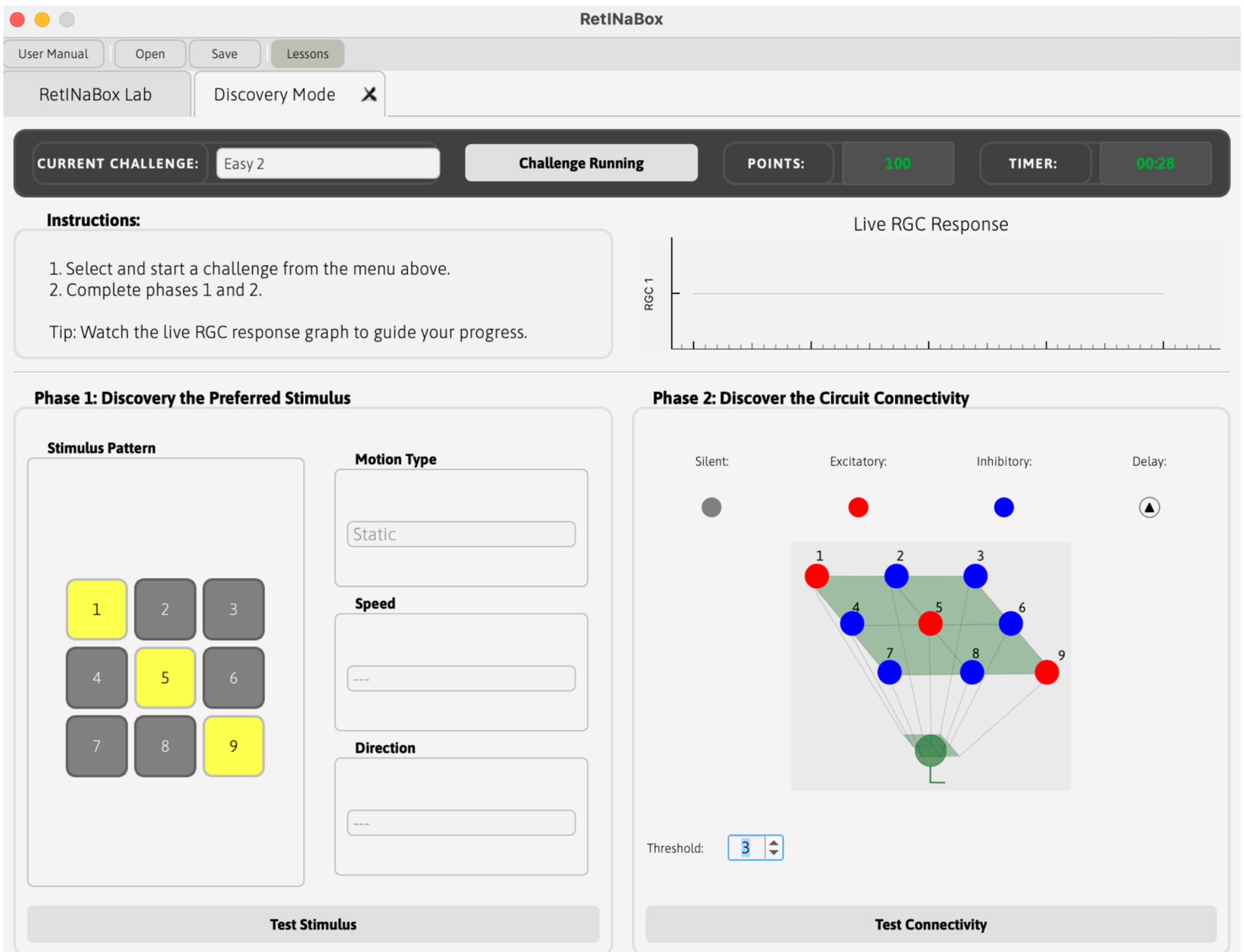


__Figure 17.__ Discovery Mode GUI. Each challenge has two phases: (1) discovering the preferred stimulus (left) and (2) discovering the circuit connectivity (right)

Each challenge in Discovery Mode has two steps:

(1) Discover the Preferred Stimulus

From the Menu tab, navigate to 'Discovery Mode' (Lessons > Lesson 4 > Discovery Mode). After selecting a mystery circuit from the drop-down menu in the GUI, your first task is to figure out what the ganglion cell responds to. Does it prefer a specific shape? A particular direction of motion? Using your Visual Stimulus Tool to test different static stimuli. Use your hand to test direction selective stimuli. The mystery circuits in RetINaBox are very selective to specific visual stimuli, so make sure you're certain before submitting your answer. Some mystery ganglion cells prefer static stimuli, some preferring moving stimuli!

(2) Discover the Circuit Connectivity

Once you've discovered what the ganglion cell is tuned to, your next challenge is to discover how it obtains this selectivity**.** How are the photoreceptors connected to the ganglion cell? What kinds of delays, polarities, or spatial arrangements of the photoreceptors give rise to the ganglion cell's selective response? *Apply the correct settings to the Connectivity Manager to match the feature selectivity you discovered.*

Good luck! *Securing grant funding for your lab depends on your success!*

Appendix

Lesson 1 Solutions: Center-Surround

Activity #1: build a spot detector with an ON-center/OFF-surround receptive field

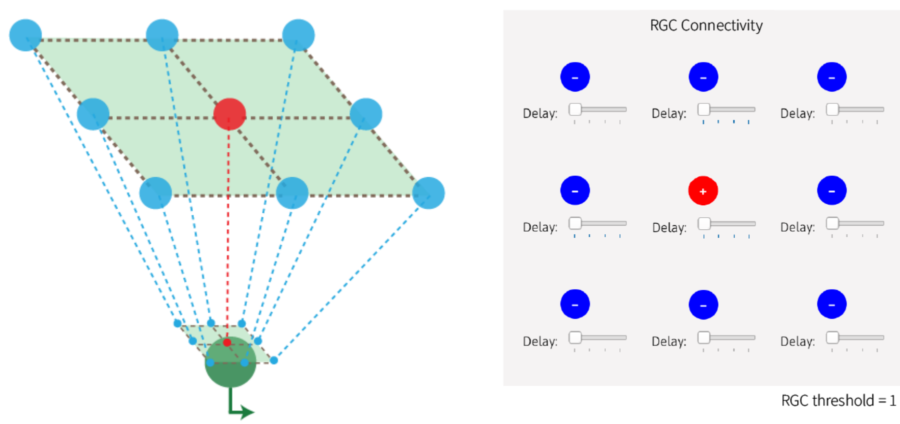
The center photoreceptor (red) is excitatory (+): it activates the ganglion cell when it detects light.

- Connect the center photoreceptor to a ganglion cell with **positive polarity** (excitatory).

The surround photoreceptors (blue) are inhibitory (-): they suppress the ganglion cell when they are activated.

- Connect each surround photoreceptor to the same ganglion cell with negative polarity (inhibitory).

Set the ganglion cell's threshold to 1. The ganglion cell will fire **only** when the center photoreceptor receives light. However, if any of the surround photoreceptors are also lit, their inhibition will cancel out the excitation, and the ganglion cell will not fire.



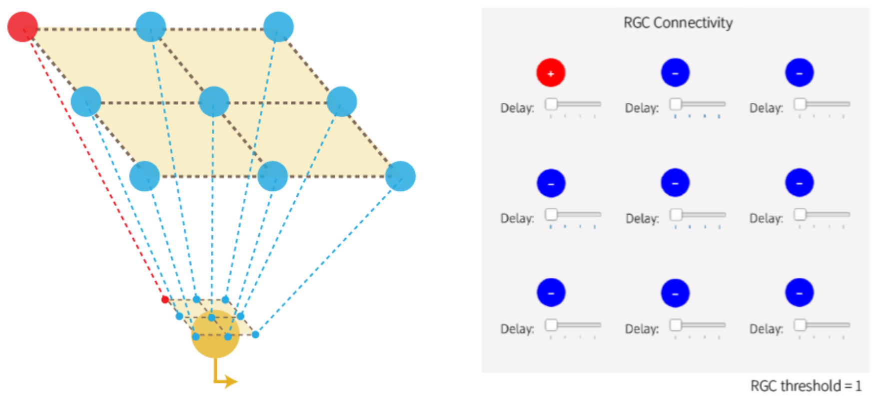
Lesson 1, Activity 1: Inputs & wiring to RGC1 (center-surround cell with center receptive field)

Activity #2: build a second spot detector with a different receptive field location

Please note that the following are just two possible examples of correct solutions. However, you could have selected any receptive field within the 3 x 3 array for either ganglion cell.

Example solution 1

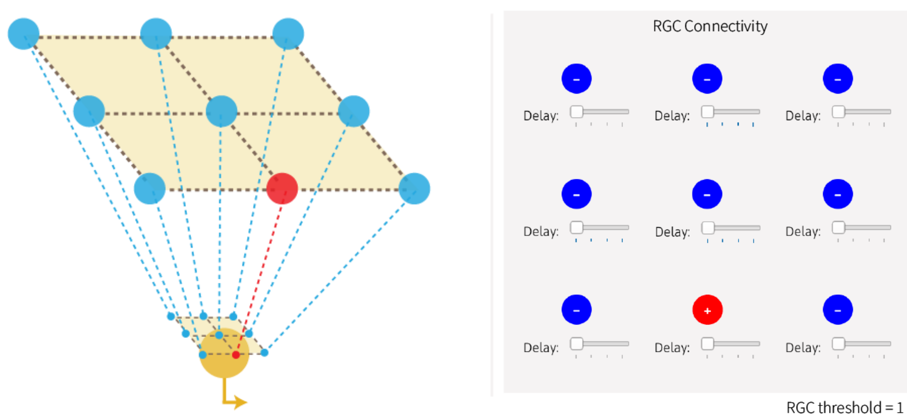
Inputs to RGC2: A corner photoreceptor (red) is excitatory (+): it activates the ganglion cell when it detects light. All other surround photoreceptors (blue) are inhibitory (–): they suppress the ganglion cell when they are activated. Set ganglion cell threshold to 1.



Lesson 1, Activity 2 – Example solution: Inputs and wiring to RGC2 (center-surround cell with a top left corner receptive field)

Example solution 2

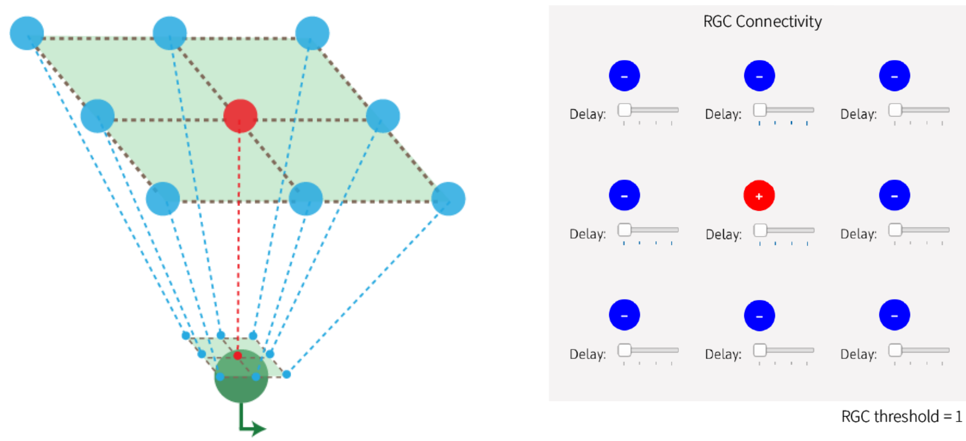
Inputs to RGC2: An edge photoreceptor (red) is excitatory (+): it activates the ganglion cell when it detects light. All other surround photoreceptors (blue) are inhibitory (-): they suppress the ganglion cell when they are activated. Set ganglion cell threshold to 1.



Lesson 1, Activity 2 – Alternative example solution: Inputs and wiring to RGC2, whose receptive field is on the edge of the array (center-surround cell with a bottom edge receptive field)

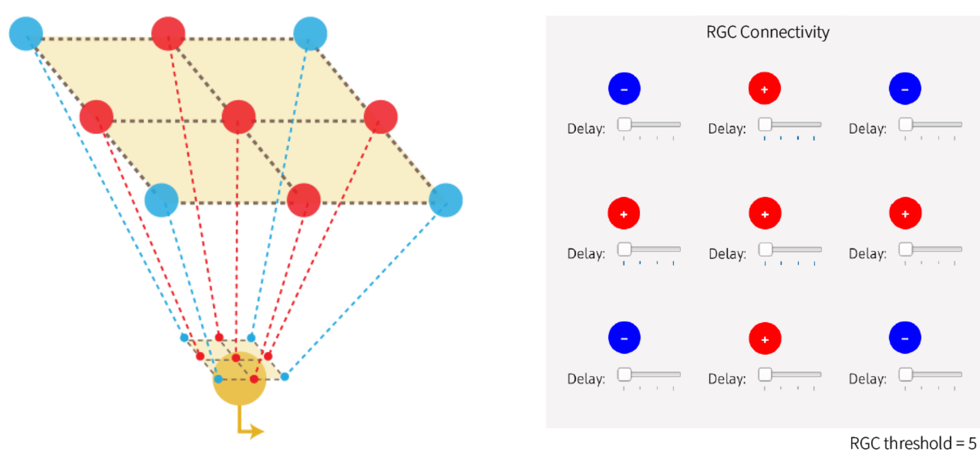
Activity #3: build two spot detectors with preferences for spots of different sizes

Inputs to RGC1 (small spot detector): as described in *Solutions to Activity #1*: The center photoreceptor (red) is excitatory (**positive polarity,** +), while all other surround photoreceptors (blue) are inhibitory (negative polarity, -). Set the ganglion cell threshold to 1. This ganglion cell will only fire in response to a small spot of light illuminating the center photoreceptor.



Lesson 1, Activity 3 – RGC1 wiring: Inputs & wiring to RGC1 (small center-surround cell with center receptive field)

Inputs to RGC2 (larger spot detector): The center photoreceptor (red) is excitatory (positive polarity, +) and will activate the ganglion cell when it detects light. However, the nearest surround photoreceptors (directly above, below, and to the sides) are also excitatory (+). The corner photoreceptors (blue) are inhibitory (negative polarity, -): they suppress the ganglion cell if the stimulus becomes too large. Set the ganglion cell's threshold to 5. This ganglion cell will fire in response to a larger spot of light illuminating the center photoreceptor and its side-surround photoreceptors. However, if the spot becomes too large and any of the corner surround photoreceptors are also lit, this added inhibition will subtract from the excitation, and the ganglion cell will not reach threshold to fire.



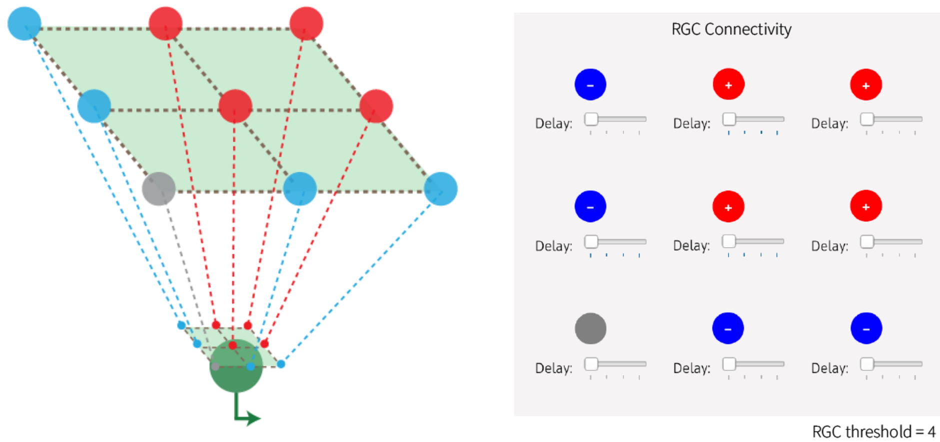
Lesson 1, Activity 3 – RGC2 wiring: Inputs & wiring to RGC2 (larger center-surround cell)

Challenge: Codebreaking with spot detectors

Challenge #1

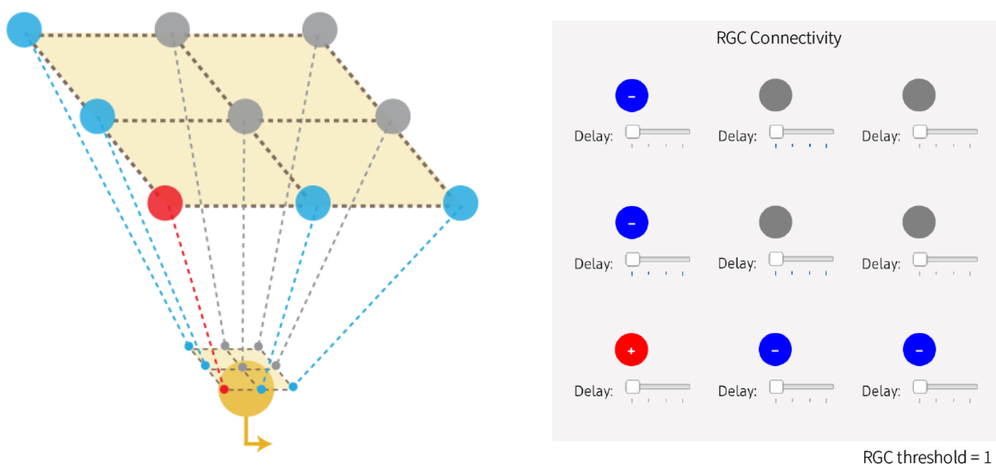
Inputs to RGC1: This center-surround cell responds only when the four photoreceptors on the top right are activated. These four photoreceptors should have positive polarity (red, excitatory,

+). All other surround photoreceptors have negative polarity (blue, inhibitory, -). The bottom left photoreceptor is left unconnected (grey), so that RGC1 and RGC2 can be co-activated. The ganglion cell threshold is set to 4.



Lesson 1, Challenge 1: Inputs & wiring to RGC1 (large spot detector with top right receptive field position)

Inputs to RGC2: This center-surround cell responds only when the bottom left photoreceptor is activated. This photoreceptor should have positive polarity (red, excitatory, +). All other surround photoreceptors have negative polarity (blue, inhibitory, -), except for the top 4 photoreceptors, corresponding RGC1's receptive field center (see above), which should be left unconnected (grey). This ensures that RGC1 and RGC2 can be co-activated. The ganglion cell threshold is set to 1.

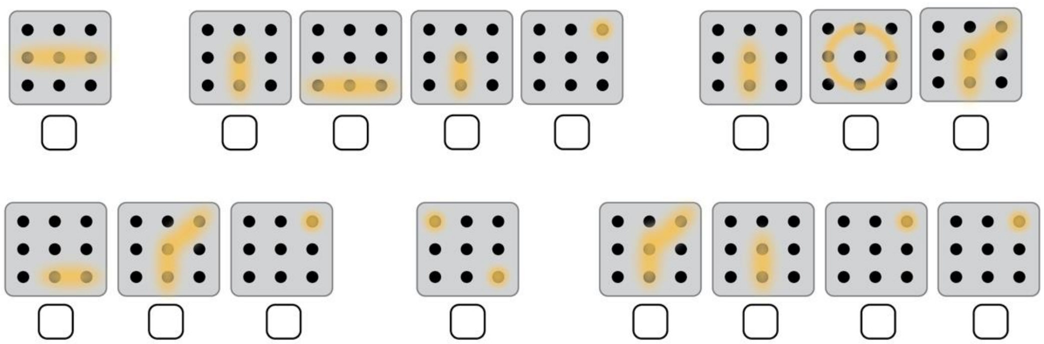


Lesson 1, Challenge 1: Inputs & wiring to RGC2 (small spot detector with bottom left receptive field)

Secret message #1: ***Dear reader, dread red area.***

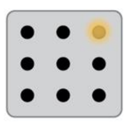
Extra problems

Challenge #2

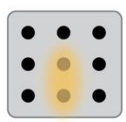


Cipher

RGC1
Preferred visual stimulus



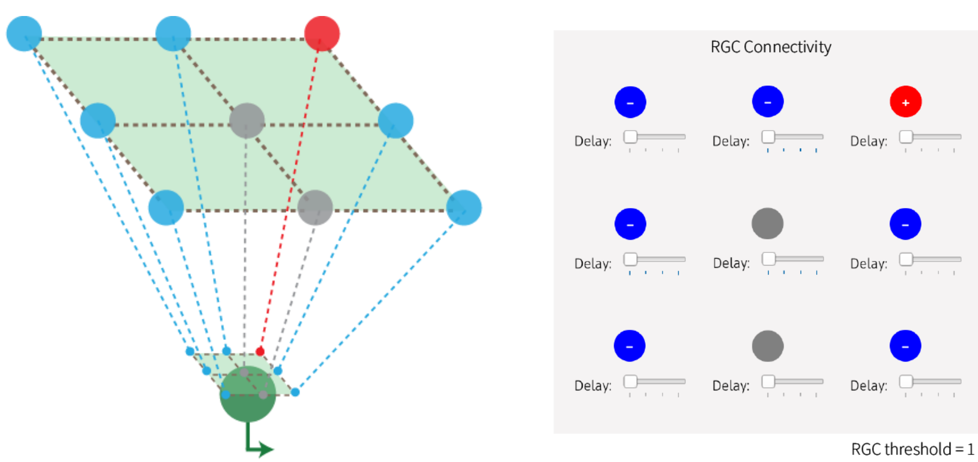
RGC2
Preferred visual stimulus



RetINaBox Output

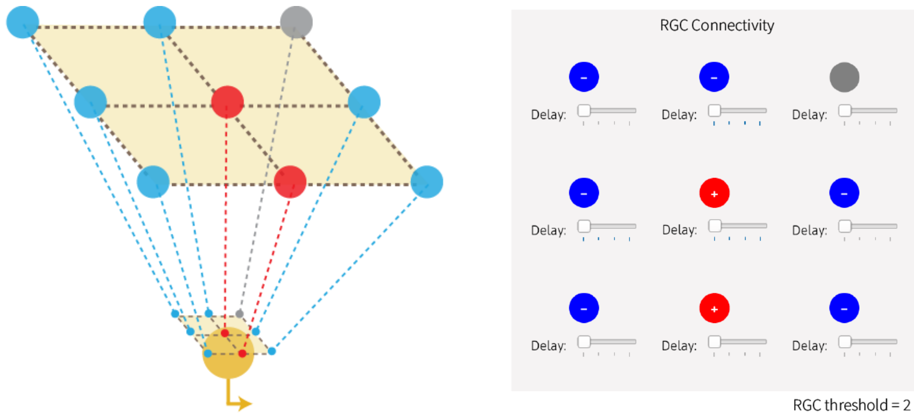
RGC1	RGC2		
0	0	=	A
1	0	=	E
0	1	=	R
1	1	=	T

Inputs to RGC1: This center-surround cell responds only when the top right corner photoreceptor is activated. This photoreceptor should have positive polarity (red, excitatory, +). All other surround photoreceptors have negative polarity (blue, inhibitory, -), except for the center and bottom photoreceptors in the middle column, which are left silent (grey), so that RGC1 and RGC2 can be co-activated. The ganglion cell threshold is set to 1.



Lesson 1, Challenge 2: Inputs & wiring to RGC1 (spot detector with top right receptive field)

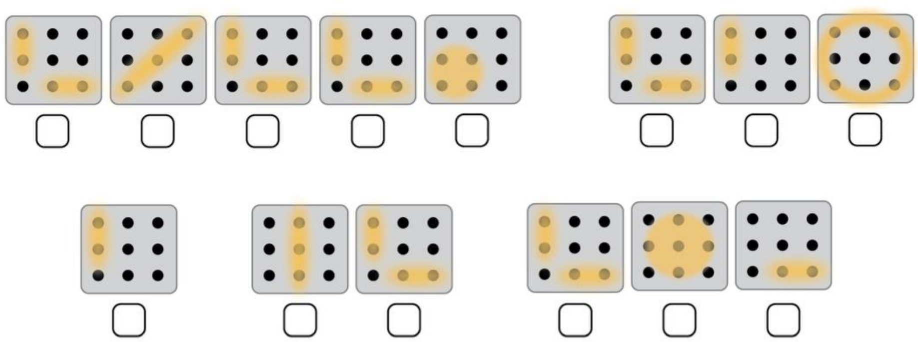
Inputs to RGC2: This cell is selective to a short vertical line segment in the center of the array. It responds only when the two photoreceptors in the bottom middle column are activated. These two photoreceptors should have positive polarity (red, excitatory, +). All other surround photoreceptors have negative polarity (blue, inhibitory, -), except for the photoreceptor connected to RGC1's center, which should be left silent. The ganglion cell threshold is set to 2.



Lesson 1, Challenge 2: Inputs & wiring to RGC2 (vertical line-segment detector)

Secret message #2: ***A rare rat ate a tree.***

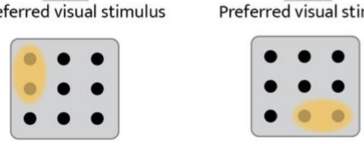
Challenge #3



Cipher

RGC1
Preferred visual stimulus

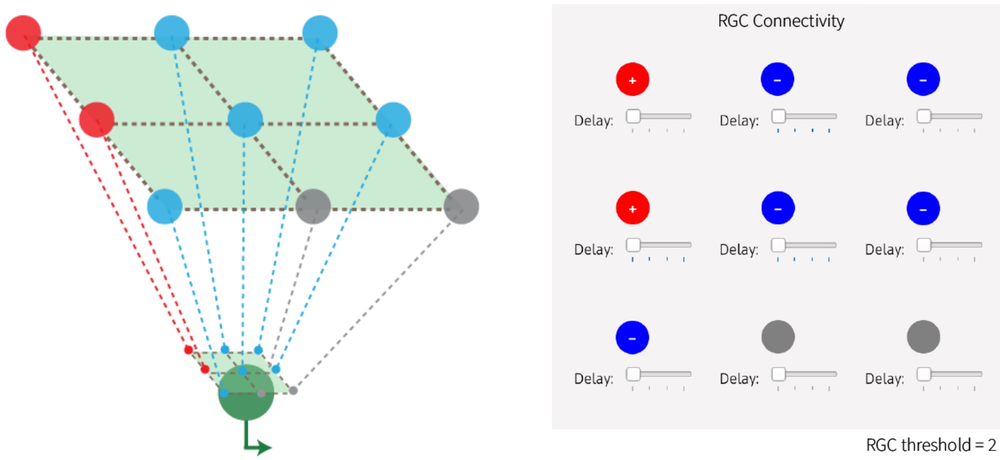
RGC2
Preferred visual stimulus



RetINaBox Output

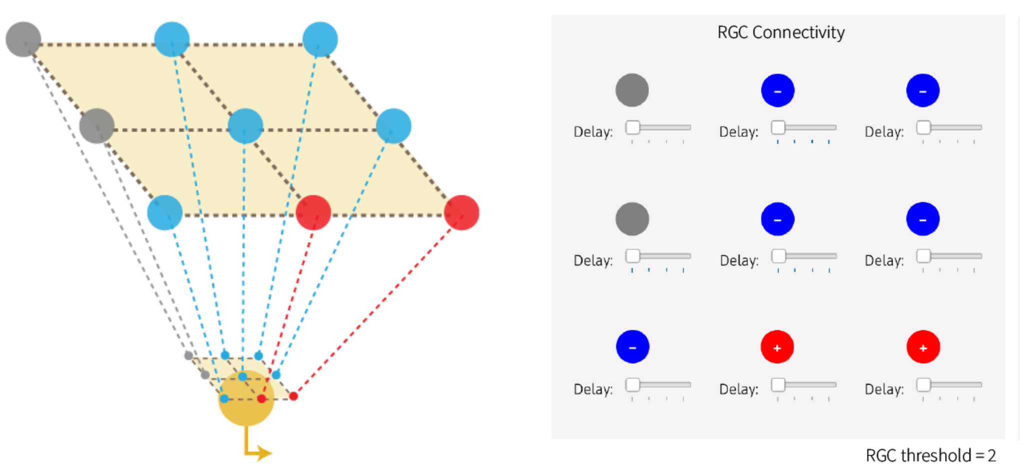
RGC1	RGC2		
0	0	=	A
1	0	=	I
0	1	=	D
1	1	=	M

Inputs to RGC1: This cell is selective to a short vertical line segment in the top left corner of the array. It responds only when the two photoreceptors in the top left column are activated. These two photoreceptors should have positive polarity (red, excitatory, +). All other surround photoreceptors have negative polarity (blue, inhibitory, -), except for the center and right photoreceptors in the bottom row, which are left silent (grey), so that RGC1 and RGC2 can be co-activated. The ganglion cell threshold is set to 2.



Lesson 1, Challenge 3: Inputs & wiring to RGC1 (vertical line-segment detector)

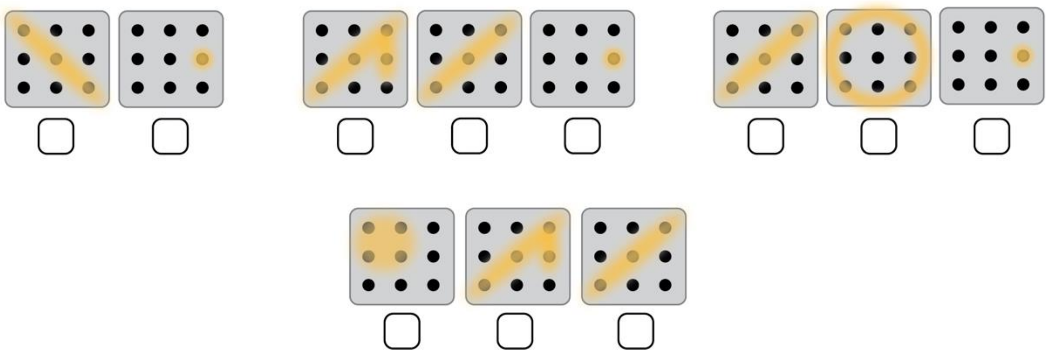
Inputs to RGC2: This cell is selective to a short horizontal line segment in the bottom right corner of the array. It responds only when the two photoreceptors in the bottom right row are activated. These two photoreceptors should have positive polarity (red, excitatory, +). All other surround photoreceptors have negative polarity (blue, inhibitory, -), except for the center and top photoreceptors in the left column, which are left silent (grey), so that RGC1 and RGC2 can be co-activated. The ganglion cell threshold is set to 2.

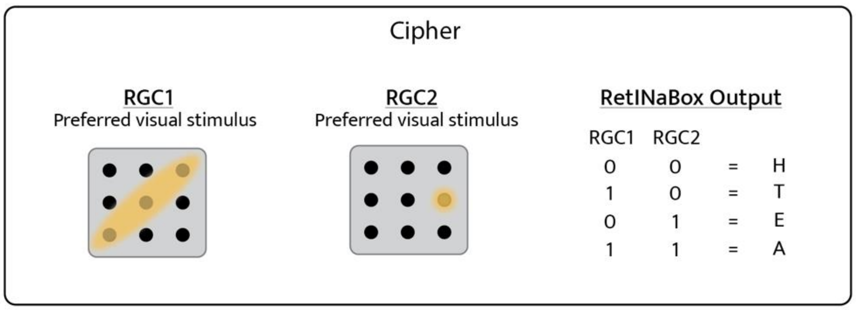


Lesson 1, Challenge 3: Inputs & wiring to RGC2 (horizontal line-segment detector)

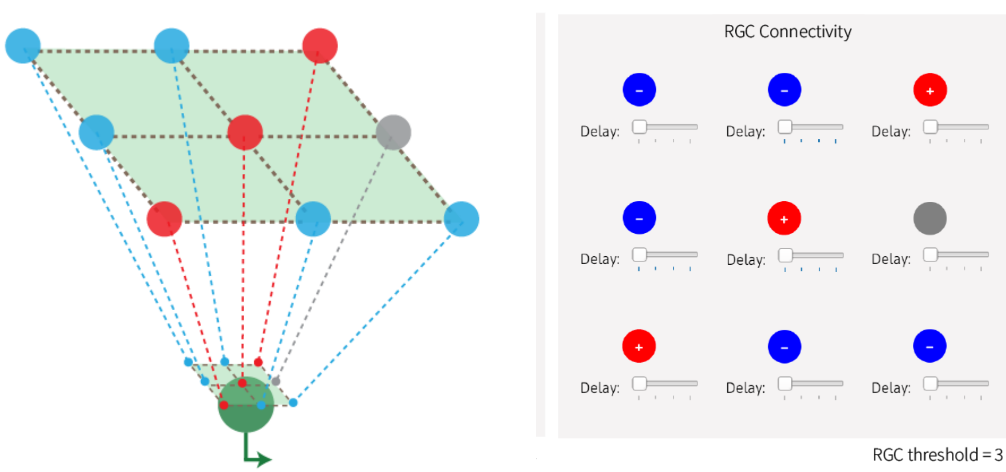
Secret message #3: ***Mamma Mia! I am mad.***

Challenge #4



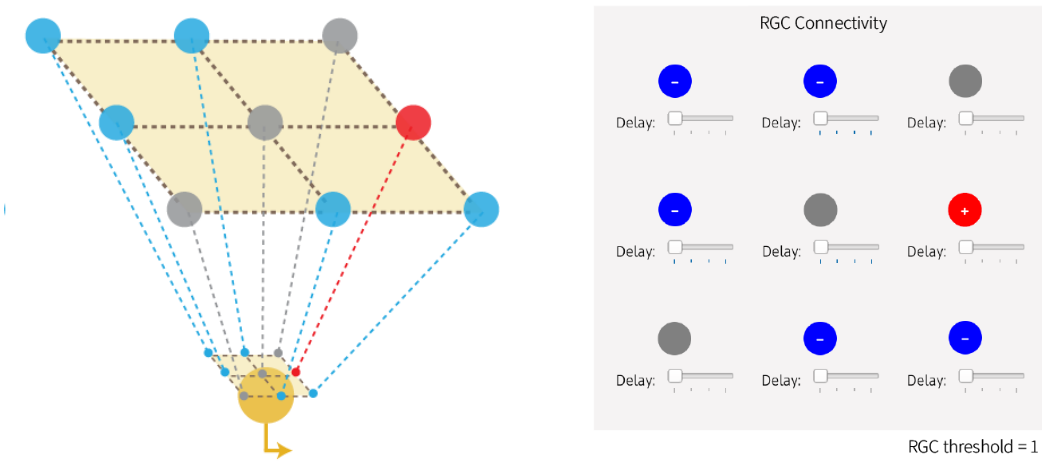


Inputs to RGC1: This orientation selective cell (introduced in Lesson 2) is selective to a diagonal line oriented at 45°. It responds only when the three photoreceptors along the 45° diagonal are activated. These photoreceptors should have positive polarity (red, excitatory, +). All other surround photoreceptors have negative polarity (blue, inhibitory, -), except for the photoreceptor connected to RGC2's center, which should be left silent. The ganglion cell threshold is set to 3.



Lesson 1, Challenge 4: Inputs & wiring to RGC1 (orientation selective cell).

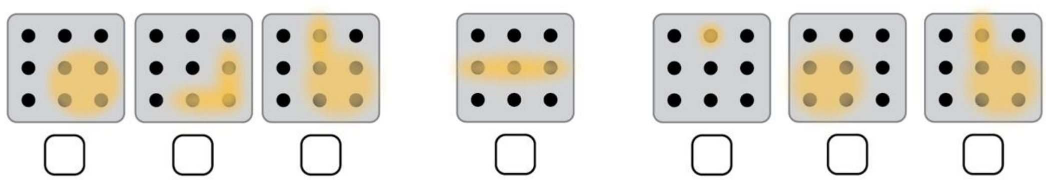
Inputs to RGC2: This center-surround cell responds only when the right photoreceptor in the middle row is activated. This photoreceptor should have positive polarity (red, excitatory, +). All other surround photoreceptors have negative polarity (blue, inhibitory, -), except for photoreceptors along the center diagonal axis (45°), which are left silent (grey), so that RGC1 and RGC2 can be co-activated. The ganglion cell threshold is set to 1.



Lesson 1, Challenge 4: Inputs & wiring to RGC2 (spot detector with right side receptive field).

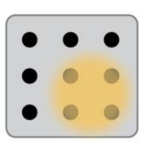
Secret message #4: ***He ate the hat.***

Challenge #5

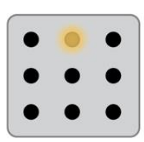


Cipher

RGC1
Preferred visual stimulus



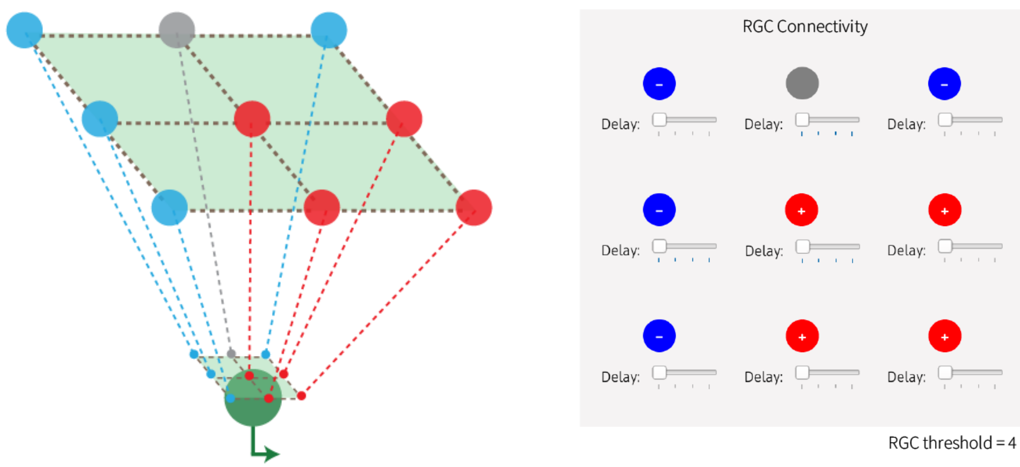
RGC2
Preferred visual stimulus



RetINaBox Output

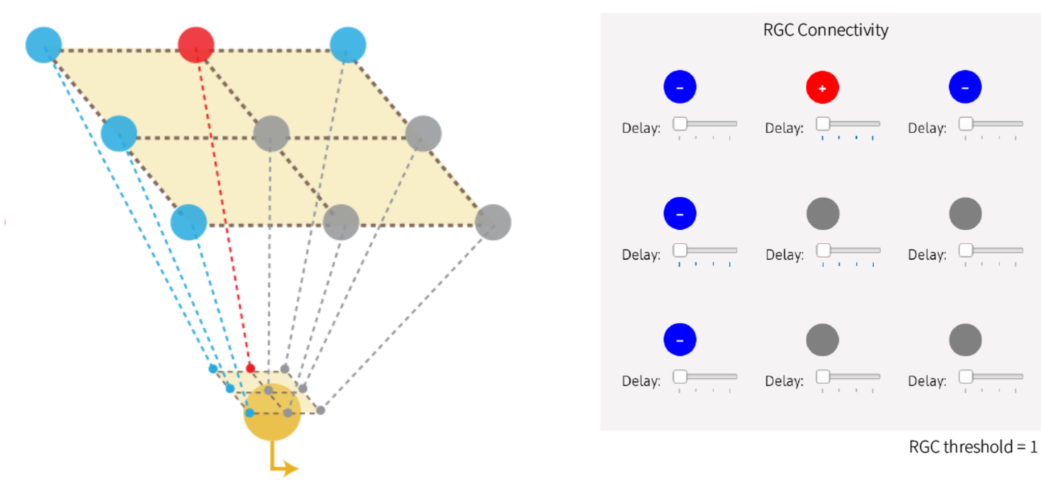
RGC1	RGC2		
0	0	=	A
1	0	=	B
0	1	=	C
1	1	=	KE

Inputs to RGC1: This center-surround cell responds only when the four photoreceptors on the bottom right are activated. These four photoreceptors should have positive polarity (red, excitatory, +). All other surround photoreceptors have negative polarity (blue, inhibitory, -), except for the photoreceptor connected to RGC2's center, which should be left silent. The ganglion cell threshold is set to 4.



Lesson 1, Challenge 5: Inputs & wiring to RGC1 (larger spot detector with bottom right receptive field)

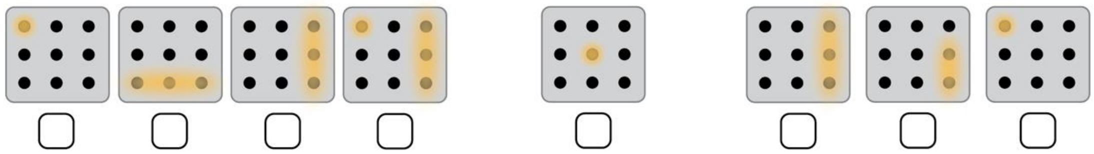
Inputs to RGC2: This center-surround cell responds only when the middle photoreceptor in the top row is activated. This photoreceptor should have positive polarity (red, excitatory, +). All other surround photoreceptors have negative polarity (blue, inhibitory, -), except for the photoreceptors connected to RGC1's center, which should be left silent. The ganglion cell threshold is set to 1.

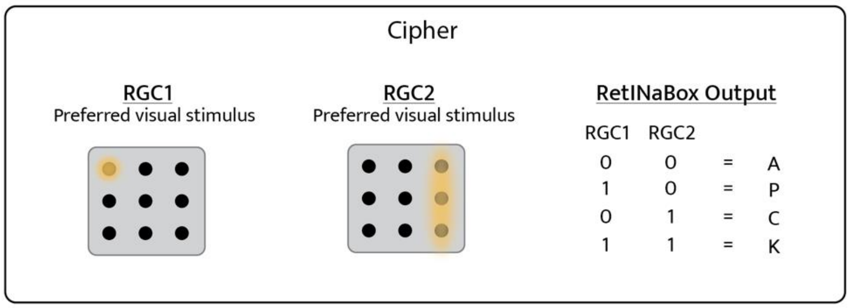


Lesson 1, Challenge 5: Inputs & wiring to RGC2 (spot detector with top center receptive field)

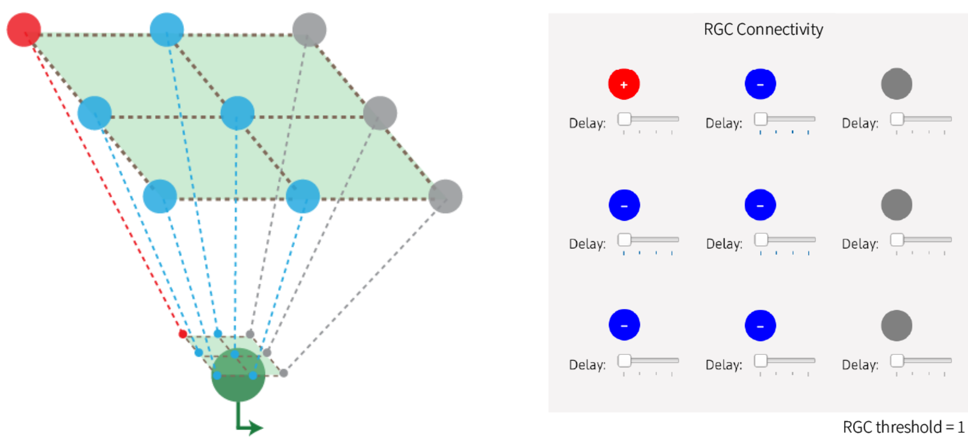
Secret message #5: ***Bake a cake.***

Challenge #6



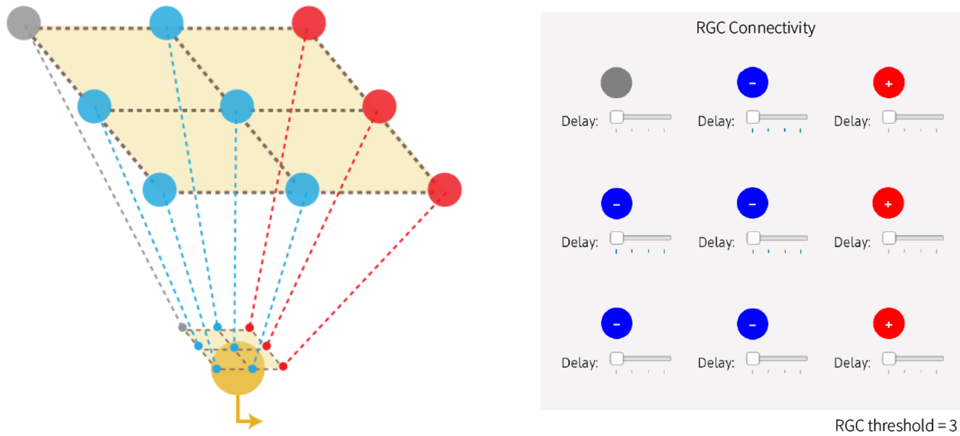


Inputs to RGC1: This center-surround cell responds only when the top left corner photoreceptor is activated. This photoreceptor should have positive polarity (red, excitatory, +). All other surround photoreceptors have negative polarity (blue, inhibitory, -), except for the photoreceptors in the right column, which are left silent (grey), so that RGC1 and RGC2 can be co-activated. The ganglion cell threshold is set to 1.



Lesson 1, Challenge 6: Inputs & wiring to RGC1 (spot detector with top left receptive field)

Inputs to GC 2: This orientation selective cell (introduced in Lesson 2) is selective to a vertical line on the right side of the photoreceptor array. It responds only when the three photoreceptors in the right column are activated. These photoreceptors should have positive polarity (red, excitatory, +). All other surround photoreceptors have negative polarity (blue, inhibitory, -), except for the photoreceptors connected to RGC2's center, which should be left silent. The ganglion cell threshold is set to 3.



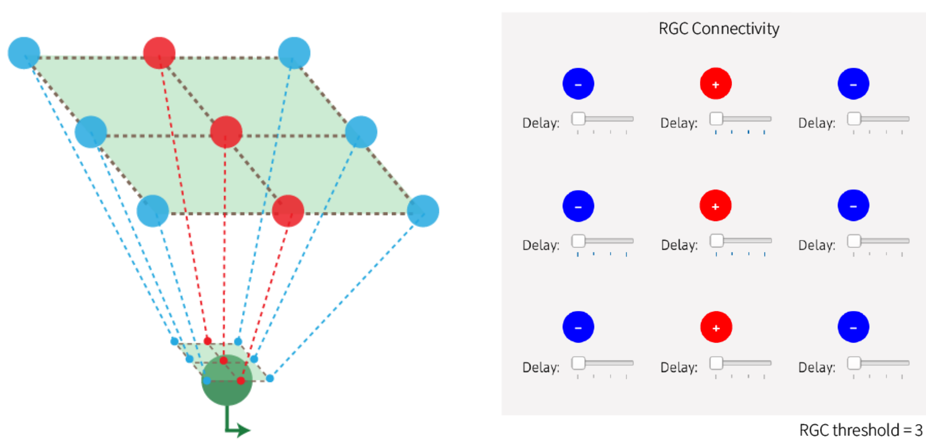
Lesson 1, Challenge 6: Inputs & wiring to RGC2 (orientation selective cell)

Secret message #6: ***Pack a cap.***

Lesson 2 Solutions: Orientation Selectivity

Activity #1: build a ganglion cell that detects a vertical line

Inputs to Ganglion Cell 1: Connect 3 adjacent photoreceptors in a straight vertical line (e.g., middle column) to the ganglion cell, with a positive (excitatory, +) polarity. Connect the 6 other surrounding photoreceptors to the same ganglion cell, with a negative (inhibitory, -) polarity. Set the ganglion cell threshold to 3, so that the ganglion cell will *only* fire when all 3 photoreceptors are activated.

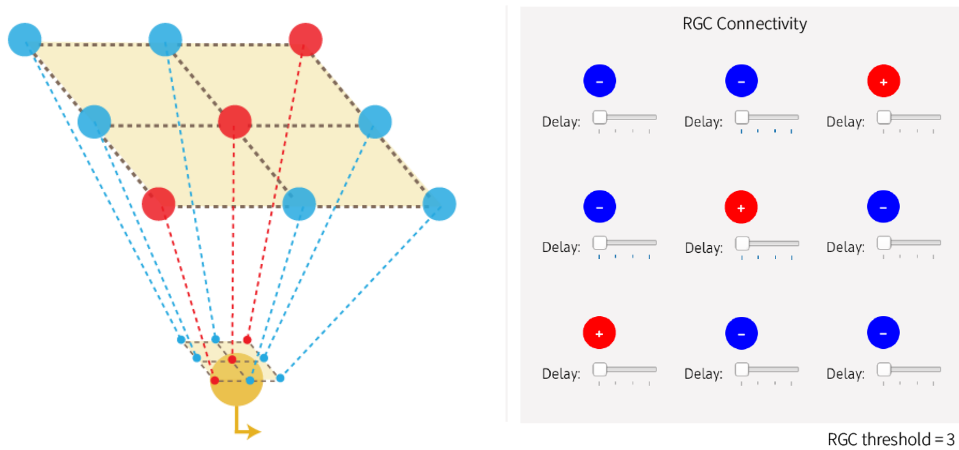


Lesson 2, Activity 1: Inputs & wiring to RGC1 (vertical orientation selective cell)

Please note that the above represents just one of three possible examples of a correct solution. However, you could have selected a vertical receptive field in the left or right column of the 3 x 3 array.

Activity #2: build a second ganglion cell that detects a diagonal line

Inputs to Ganglion Cell 2: Connect 3 photoreceptors along the diagonal line to the ganglion cell, with a positive (excitatory, +) polarity. Connect the 6 other off-diagonal photoreceptors to the same ganglion cell, with a negative (inhibitory, -) polarity. Set the ganglion cell threshold to 3, so that the ganglion cell will *only* fire when all 3 photoreceptors are activated but will be inhibited if any of the off-diagonal photoreceptors are activated.

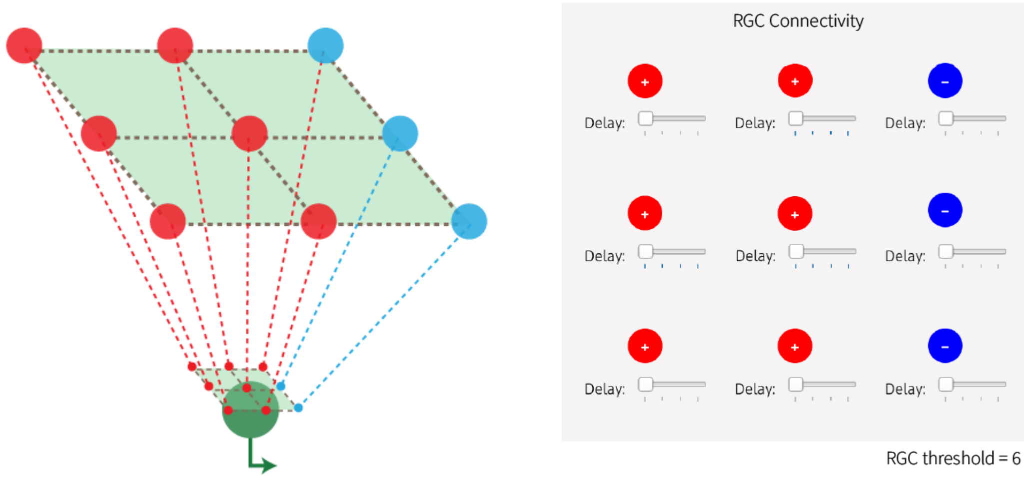


Lesson 2, Activity 2: Inputs & wiring to RGC2 (diagonal orientation selective cell)

Please note that the above represents just one of two possible examples of a correct solution. However, you could have selected a diagonal receptive field oriented at 135º (i.e., the other diagonal).

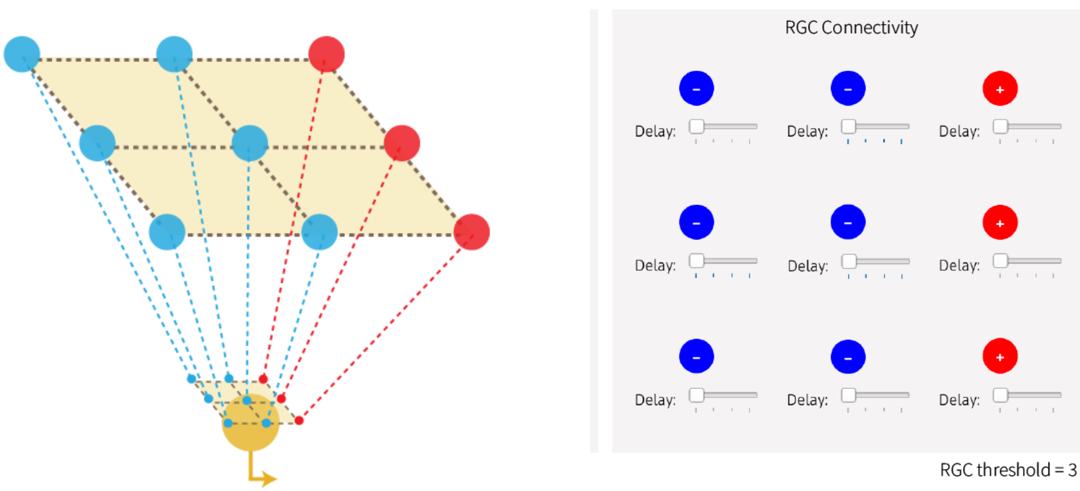
Activity #3: build two ganglion cells that detect vertical lines of different thicknesses

Inputs to Ganglion Cell 1: connect two adjacent columns of 3 photoreceptors in a vertical line (for example, middle column + side column) to Ganglion Cell 1, with a positive (excitatory, -) polarity. Connect the 3 other surround photoreceptors to the same ganglion cell, with a negative (inhibitory, -) polarity. Set the ganglion cell threshold to 6, so that the ganglion cell will *only* fire when all 6 photoreceptors are activated.



Lesson 2, Activity 3: Inputs & wiring to RGC1 (thick vertical orientation selective cell)

Inputs to Ganglion Cell 2: connect one column of 3 photoreceptors in a vertical line (for example, right column) to Ganglion Cell 2, with a positive (excitatory, +) polarity. Connect the 6 other surrounding photoreceptors to the same ganglion cell, with a negative (inhibitory, -) polarity. Set the ganglion cell threshold to 3, so that the ganglion cell will *only* fire when all 3 photoreceptors are activated.



Lesson 2, Activity 3: Inputs & wiring to RGC2 (thin vertical orientation selective cell)

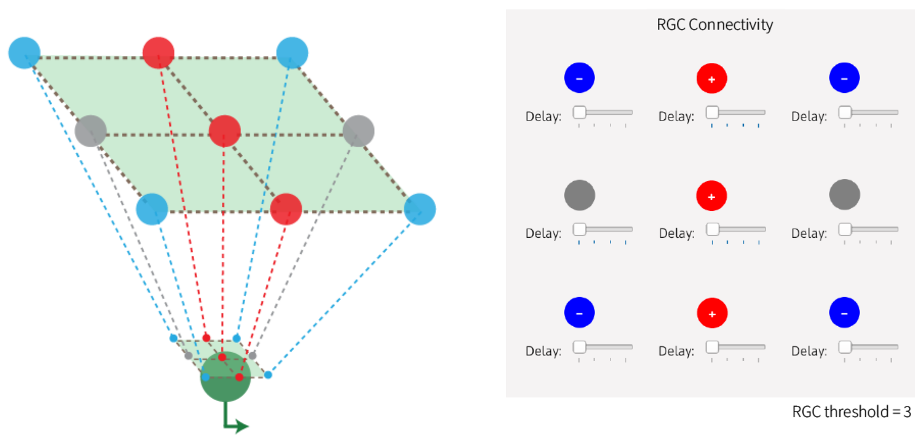
Please note that the above represents one of several possible examples of a correct solution. You could have configured each ganglion cell with vertical receptive field in various locations (i.e., shifted left or right).

Challenge #1: build a shape detector with orientation selective receptive fields

Please note that the solution below represents one of several possible correct solutions. You could have chosen any potential shape combining two straight lines of any orientation (for example, an X, a T, or an L - in any orientation). The below solution will configure a shape detector responsive to an 'X' shape.

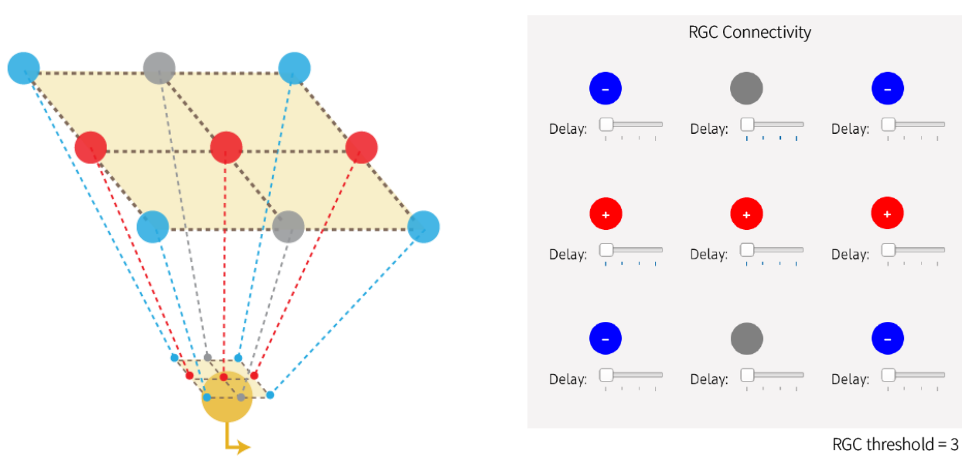
Each of the ganglion cells should be responsive to a line in a different position/orientation. They should both fire when the shape is presented (i.e. each ganglion cell must not be silenced when the other ganglion cell is active).

Inputs to Ganglion Cell 1: To make a cross shape, we would like Ganglion Cell 1 to be responsive to a vertical line in the middle of the photoreceptor array. Connect 3 adjacent photoreceptors (e.g. a vertical line) to a ganglion cell with a positive (excitatory, +) polarity, so that it fires only when all 3 photoreceptors are activated (i.e., when a vertical bar of light is present in the center of the array). The cells in the corner of the array should be inhibitory (-), while the two left and right cells in the center row should be inactivated (grey). This will make the cell orientation selective but also continue to respond when Ganglion Cell 2 (see below) is activated.



Lesson 2, Challenge 1: Inputs & wiring to RGC1 (vertical *orientation selective cell)*

Inputs to Ganglion Cell 2: To make a cross shape, we would like Ganglion Cell 2 to be responsive to a horizontal line in the middle of the photoreceptor array. Connect 3 adjacent photoreceptors (e.g. a horizontal line) to the second ganglion cell with a positive (excitatory, +) polarity, so that it fires only when all 3 photoreceptors are activated (i.e., when a horizontal bar of light is present in the center of the array). Similar to above, adding inhibition to the corner photoreceptor connections (negative polarity, -) while inactivating the top and bottom cells in the middle column will make the cell orientation selective, but still allow it to respond when RGC1 is active.



Lesson 2, Challenge 1: Inputs & wiring to RGC2 (horizontal orientation selective cell)

Lesson 3 Solutions: Direction Selectivity

Note: Depending on the time delays you've assigned to each photoreceptor, you may need to test different stimulus speeds to observe the ganglion cell firing specifically in one direction. The circuit will work most robustly when the speed of motion is tailored to the timing of the delays, allowing all preferred-direction inputs to summate at the ganglion cell simultaneously during preferred-direction motion, and allowing null-direction inhibition to effectively cancel excitation during null-direction motion.

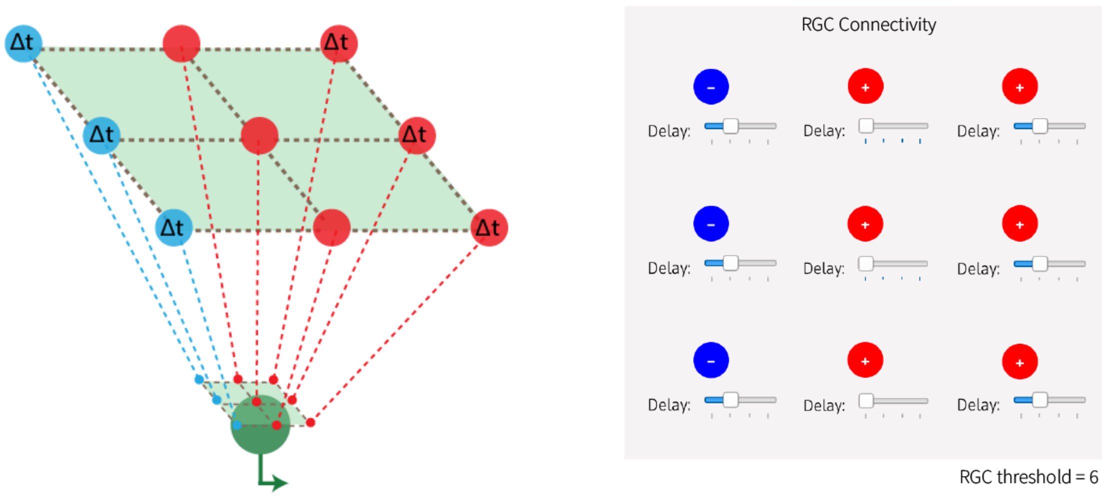
Activity #1: build a left-moving direction selective ganglion cell ←

The ganglion cell receives input from two full columns of excitatory photoreceptors (positive polarity) and one full column of inhibitory photoreceptors (negative polarity).

- Left-most photoreceptor column (inhibitory, -): short/medium time delay
- Middle photoreceptor column (excitatory, +): No time delay
- Right-most photoreceptor column (excitatory, +): short/medium time delay

Set the **ganglion cell threshold to 6.** This ensures that the cell will only fire when both columns of excitatory photoreceptors (6 photoreceptors in total) are activated in sync, i.e., when the direction of motion is leftwards, and the timing aligns perfectly for input summation.

This configuration causes the ganglion cell to fire only when a stimulus moves leftward across the array. The stimulus sequentially activates the rightmost, middle, and finally left column photoreceptors. The delays are configured so that the signals from the two excitatory columns arrive at the ganglion cell simultaneously **only** during leftward motion, allowing the cell to reach threshold and fire. The inhibitory column's input, being delayed, arrives too late to interfere with the ganglion cell's response. If the stimulus moves rightward (i.e., the opposite direction to the ganglion cell's preferred direction), the inhibitory column will summate with the excitatory column, cancelling out excitation and preventing the ganglion cell from firing. Furthermore, the two columns of excitatory inputs will be activated out of phase with one another for rightward motion. **note that if you simply stimulate the 6 positively connected photoceptors (while not stimulating the 3 negatively connected photoreceptors) with a static stimulus, the ganglion cell will eventually turn on as well (similar to what happens for many direction selective ganglion cells in the brain which can sometimes be activated by both preferred direction moving and static stimuli).*



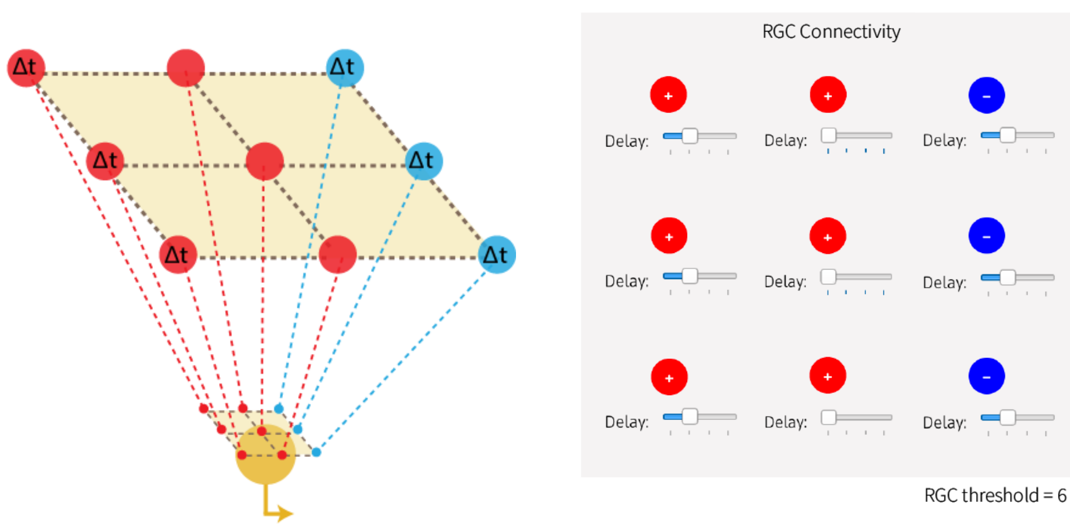
Lesson 3, Activity 1: Inputs & wiring to RGC1 (left-moving direction selective cell)

Activity #2: build a right-moving direction selective ganglion cell →

The ganglion cell receives input from two full columns of excitatory photoreceptors (positive polarity) and one full column of inhibitory photoreceptors (negative polarity).

- Left-most photoreceptor column (excitatory, +): short/medium time delay
- Middle photoreceptor column (excitatory, +): No time delay
- Right-most photoreceptor column (inhibitory, -): short/medium time delay

Set the **ganglion cell threshold to 6.** This ensures that the cell will only fire when both columns of excitatory photoreceptors (6 photoreceptors in total) are activated in sync, i.e., when the direction of motion is rightwards, and the timing aligns perfectly for input summation. Please refer to *Activity #1 Solution* for a detailed explanation of time-aligned input summation.



Lesson 3, Activity 2: Inputs & wiring to RGC2 (right-moving direction selective cell)

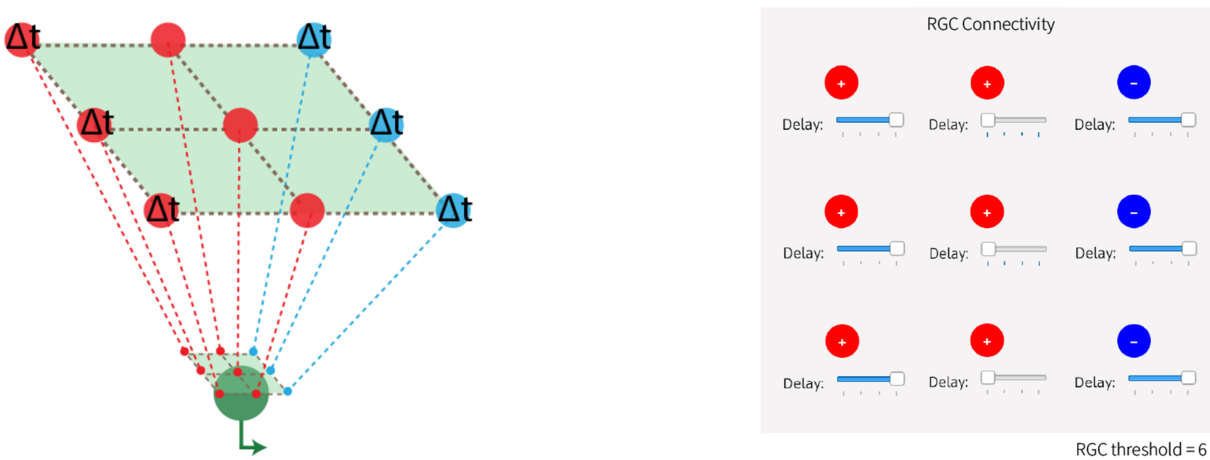
Activity #3: build a slow vs. fast motion preferring direction selective ganglion cell →

The key to solving this problem is the **magnitude of the time delays** imposed on the circuits seen in Activity #1 (right-direction selective cell).

Each ganglion cell receives input from two full columns of excitatory photoreceptors (positive polarity) and one full column of inhibitory photoreceptors (negative polarity). Set each **ganglion cell threshold to 6.** This ensures that the cell will only fire when both columns of excitatory photoreceptors (6 photoreceptors in total) are activated in sync.

Inputs to RGC1 (slow-moving → directions-selective cell):

- Left-most photoreceptor column (excitatory, +): long time delay
- Middle photoreceptor column (excitatory, +): no time delay
- Right-most photoreceptor column (inhibitory, -): long time delay

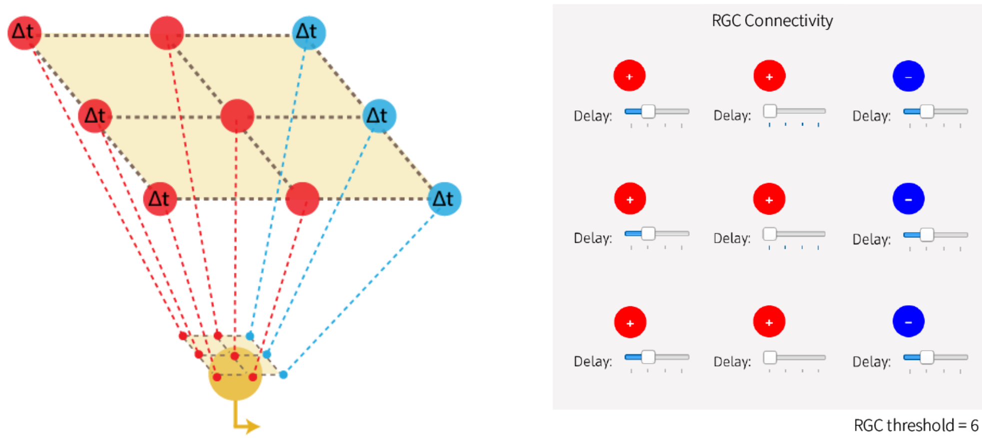


Lesson 3, Activity 3: Inputs & wiring to RGC1 (slow right-moving direction selective cell)

Inputs to RGC2 (fast-moving → directions-selective cell):

- Left-most photoreceptor column (excitatory, +): short time delay
- Middle photoreceptor column (excitatory, +): no time delay
- Right-most photoreceptor column (inhibitory, -): short time delay

A shorter time delay creates a smaller time window for inputs to summate, so the stimulus must move faster to activate the ganglion cell. Conversely, a longer time delay creates a wider summation window, allowing the cell to respond to slower motion. Please refer to *Activity #1 Solution* for a detailed explanation of time-aligned input summation.

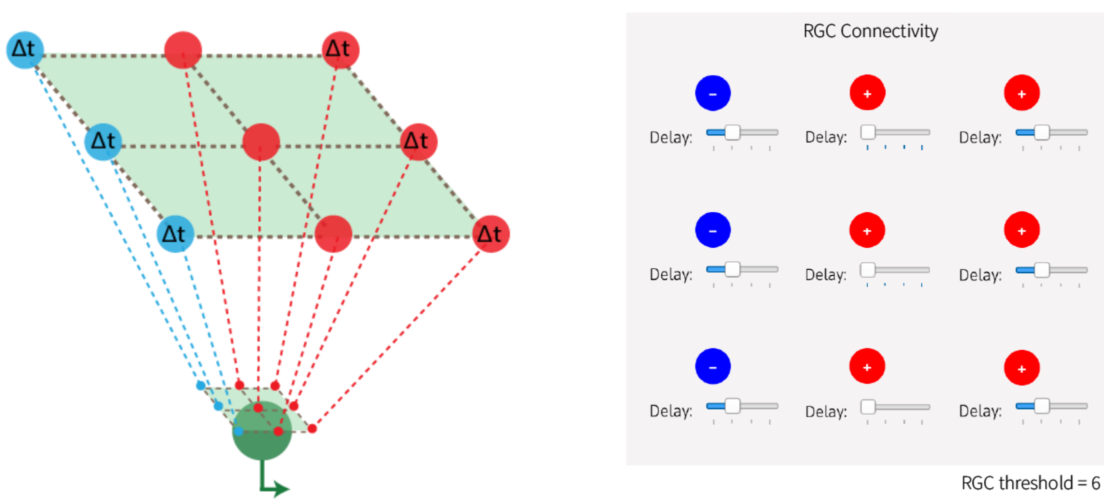


Lesson 3, Activity 3: Inputs & wiring to RGC2 (fast right-moving direction selective cell)

Challenge: Block breaking with direction selective circuits

Inputs to RGC1 🡠: the ganglion cell receives input from two full columns of excitatory photoreceptors (positive polarity) and one full column of inhibitory photoreceptors (negative polarity). Set the **ganglion cell threshold to 6.**

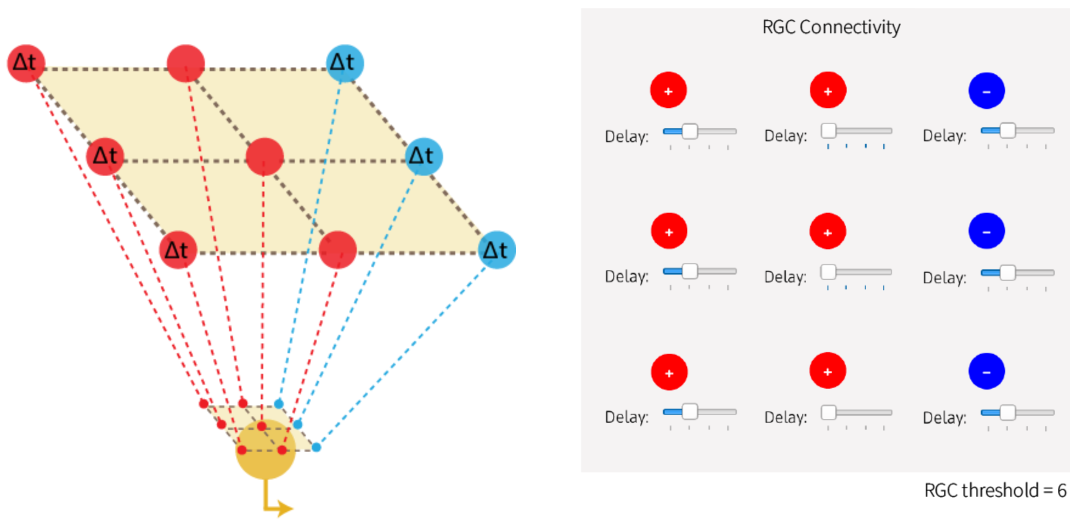
- Left-most photoreceptor column (inhibitory, -): short time delay
- Middle photoreceptor column (excitatory, +): No time delay
- Right-most photoreceptor column (excitatory, +): short time delay



Lesson 3, Challenge 1: Inputs & wiring to RGC1 (left-moving direction selective cell)

Inputs to RGC2 🡢 : the ganglion cell receives input from two full columns of excitatory photoreceptors (positive polarity) and one full column of inhibitory photoreceptors (negative polarity). Set the **ganglion cell threshold to 6.**

- Left-most photoreceptor column (excitatory, +): short time delay
- Middle photoreceptor column (excitatory, +): No time delay
- Right-most photoreceptor column (inhibitory, -): short time delay



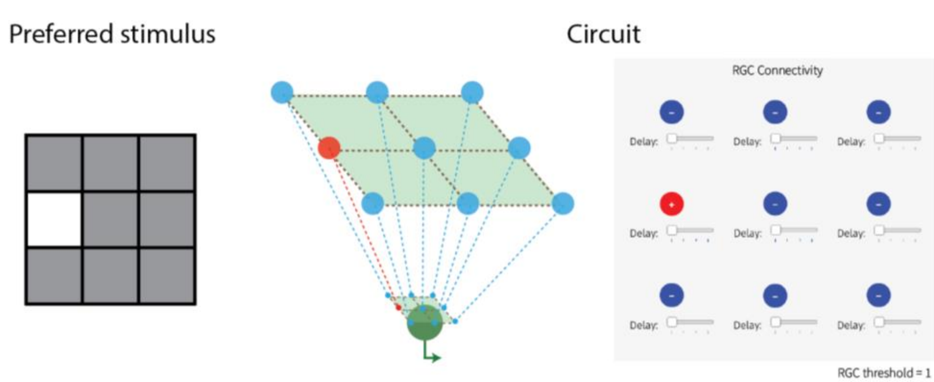
Lesson 3, Activity 4: Inputs & wiring to RGC2 (right-moving direction selective cell)

Discovery Mode

Easy

<u>*Easy 1:* Center-surround cell</u>

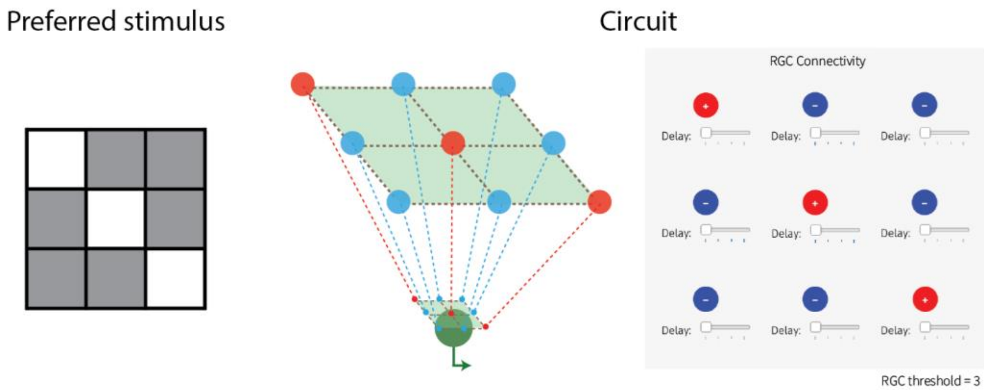
- Preferred stimulus: static spot of light on the left edge of the receptive field
- Ganglion cell threshold: 1



Lesson 4, Easy 1: Preferred stimulus (left) and wiring (right) to Easy 1 mystery circuit

<u>*Easy 2:* Orientation selective cell</u>

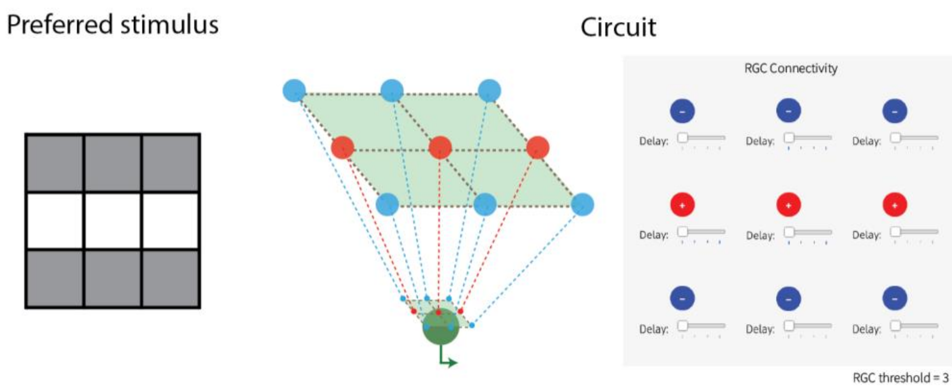
- Preferred stimulus: static diagonal line (135°) in the center of the receptive field
- Ganglion cell threshold: 3



Lesson 4, Easy 2: Preferred stimulus (left) and wiring (right) to Easy 2 mystery circuit

<u>*Easy 3:* Orientation selective cell</u>

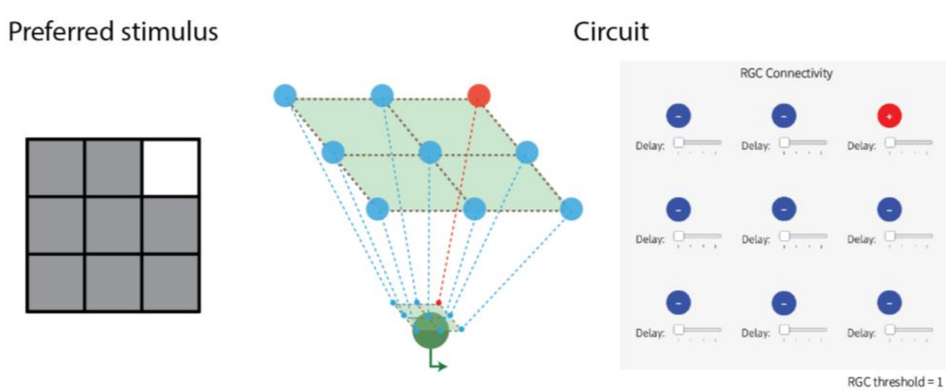
- Preferred stimulus: static horizontal line in the center field
- Ganglion cell threshold: 3



Lesson 4, Easy 3: Preferred stimulus (left) and wiring (right) to Easy 3 mystery circuit

<u>*Easy 4:* Center-surround cell</u>

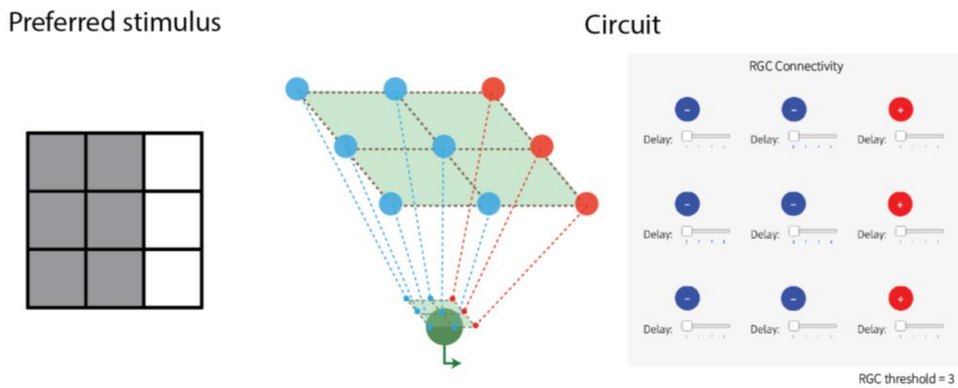
- Preferred stimulus: static spot of light on the top right corner of the receptive field
- Ganglion cell threshold: 1



Lesson 4, Easy 4: Preferred stimulus (left) and wiring (right) to Easy 4 mystery circuit

Easy 5: Orientation selective cell

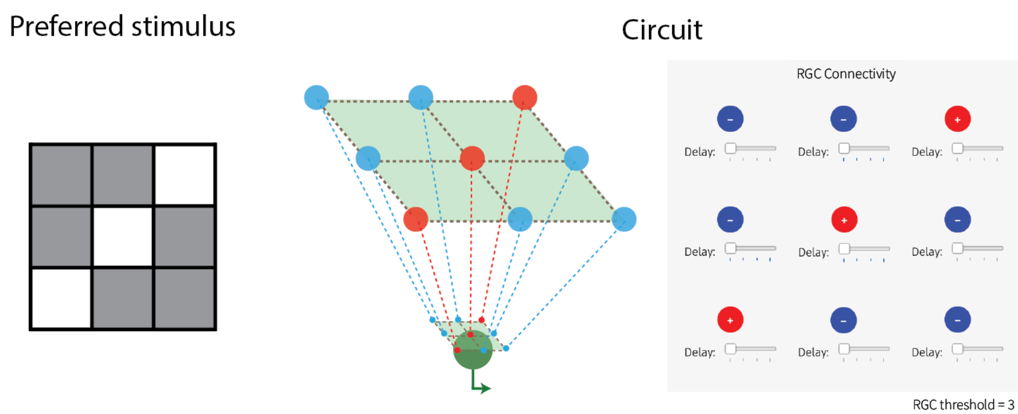
- Preferred stimulus: static vertical line on the right edge of the receptive field
- Ganglion cell threshold: 3



Lesson 4, Easy 5: Preferred stimulus (left) and wiring (right) to Easy 5 mystery circuit

Easy 6: Orientation selective cell

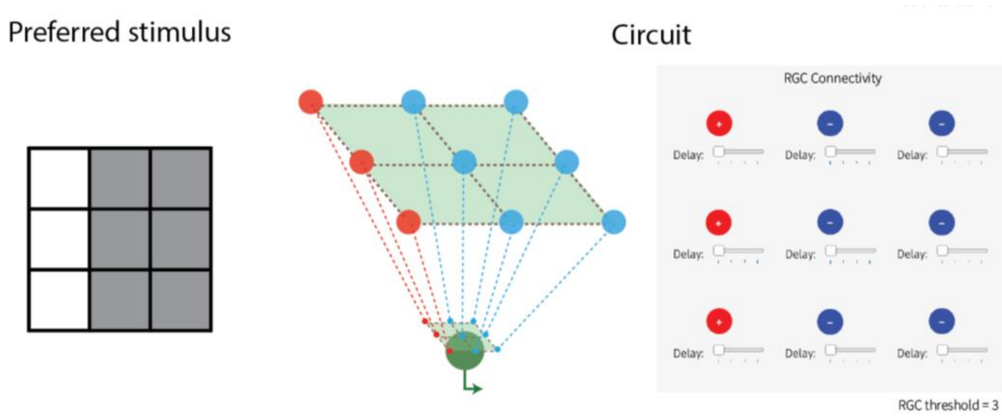
- Preferred stimulus: static diagonal line (45°) in the center of the receptive field
- Ganglion cell threshold: 3



Lesson 4, Easy 6: Preferred stimulus (left) and wiring (right) to Easy 6 mystery circuit

Easy 7: Orientation selective cell

- Preferred stimulus: static vertical line on the left edge of the receptive field
- Ganglion cell threshold: 3

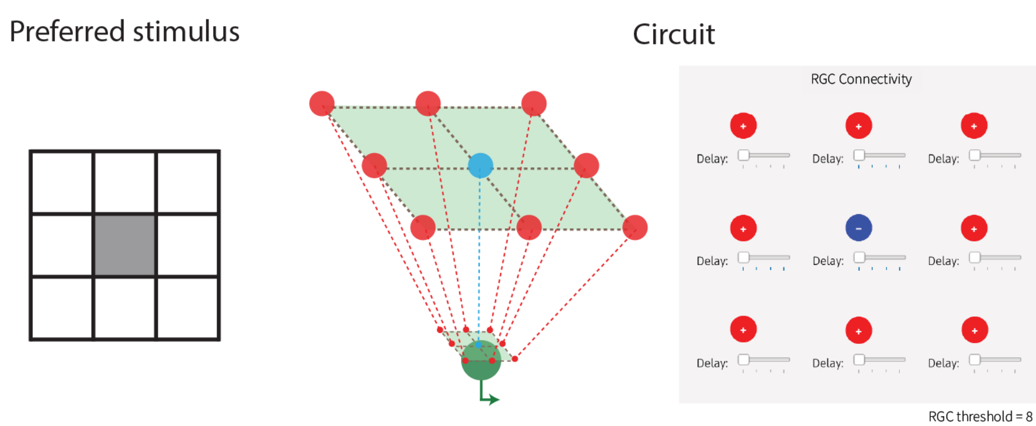


Lesson 4, Easy 7: Preferred stimulus (left) and wiring (right) to Easy 7 mystery circuit

Medium

<u>*Medium 1: Ring-selective cell*</u>

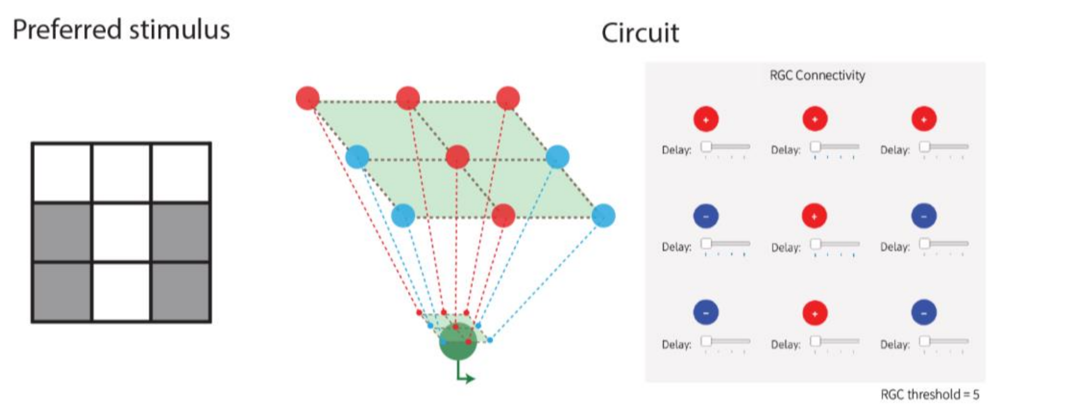
- Preferred stimulus: ring of light (no light in the center of the receptive field)
- Ganglion cell threshold: 8



Lesson 4, Medium 1: Preferred stimulus (left) and wiring (right) to Medium 1 mystery circuit

<u>*Medium 2:* Shape (T) selective cell</u>

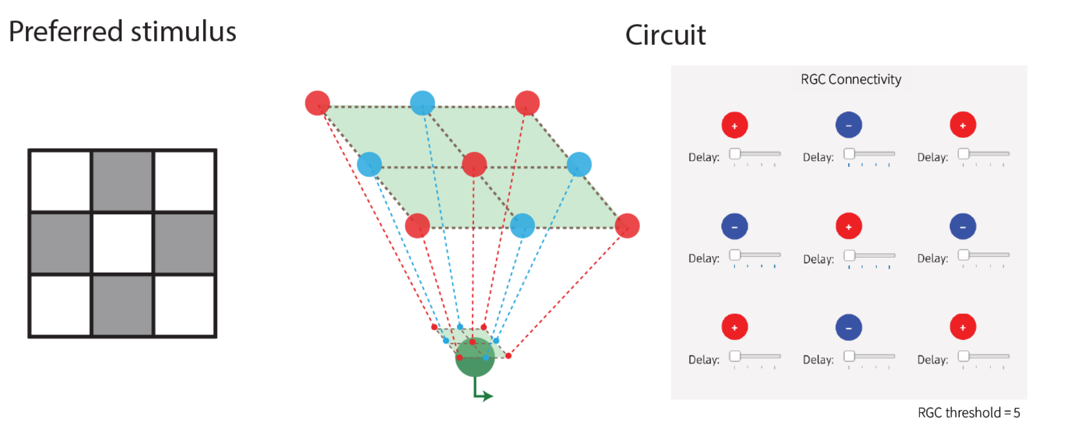
- Preferred stimulus: T-shape
- Ganglion cell threshold: 5



Lesson 4, Medium 2: Preferred stimulus (left) and wiring (right) to Medium 2 mystery circuit

<u>*Medium 3:* Shape (X) selective cell</u>

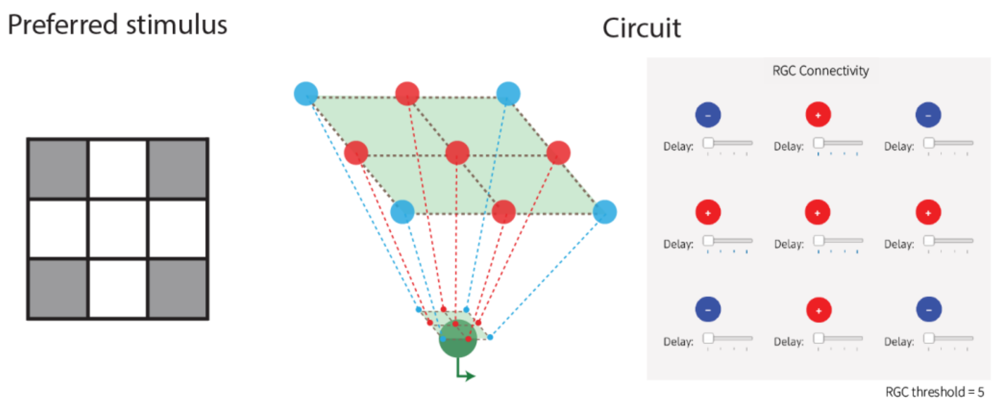
- Preferred stimulus: X-shape in the center of the receptive field
- Ganglion cell threshold: 5



Lesson 4, Medium 3: Preferred stimulus (left) and wiring (right) to Medium 3 mystery circuit

<u>*Medium 4:* Shape (+) selective</u>

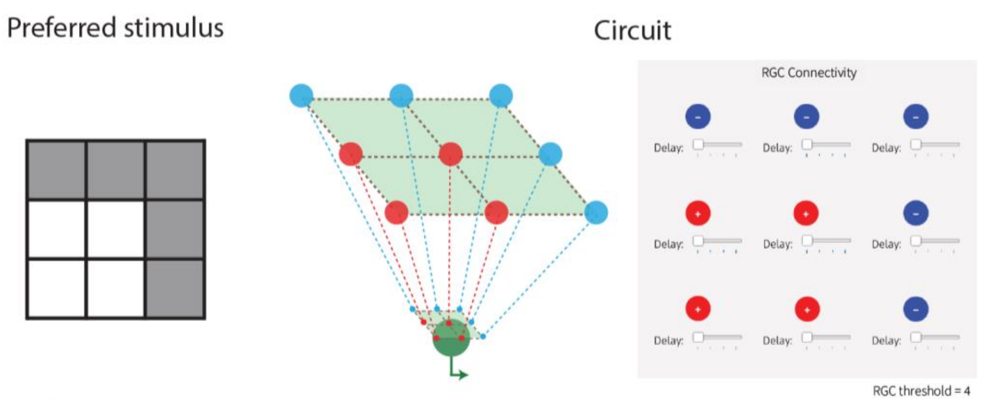
- Preferred stimulus: + - shape (or a medium-sized spot of light) in the center of the receptive field
- Ganglion cell threshold: 5



Lesson 4, Medium 4: Preferred stimulus (left) and wiring (right) to Medium 4 mystery circuit

<u>*Medium 5:* Center-surround cell</u>

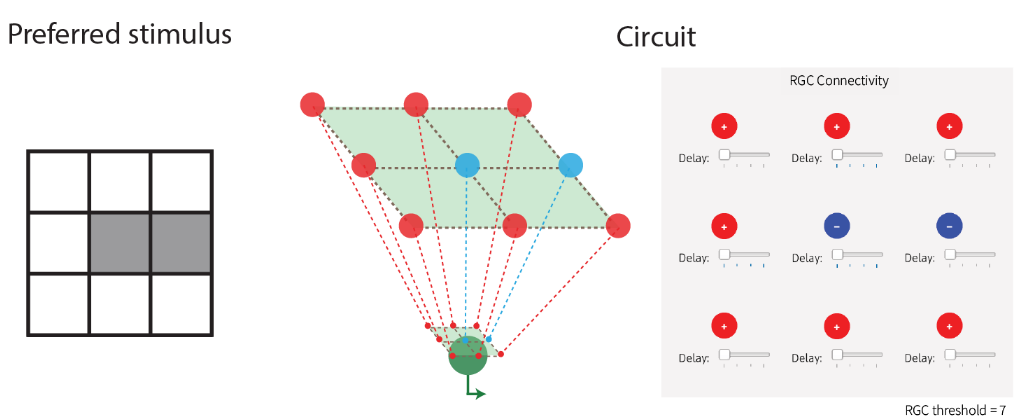
- Preferred stimulus: Medium-sized spot of light with a bottom-left receptive field
- Ganglion cell threshold: 4



Lesson 4, Medium 5: Preferred stimulus (left) and wiring (right) to Medium 5 mystery circuit

<u>*Medium 6:* Shape (C) selective cell</u>

- Preferred stimulus: C-shape
- Ganglion cell threshold: 7

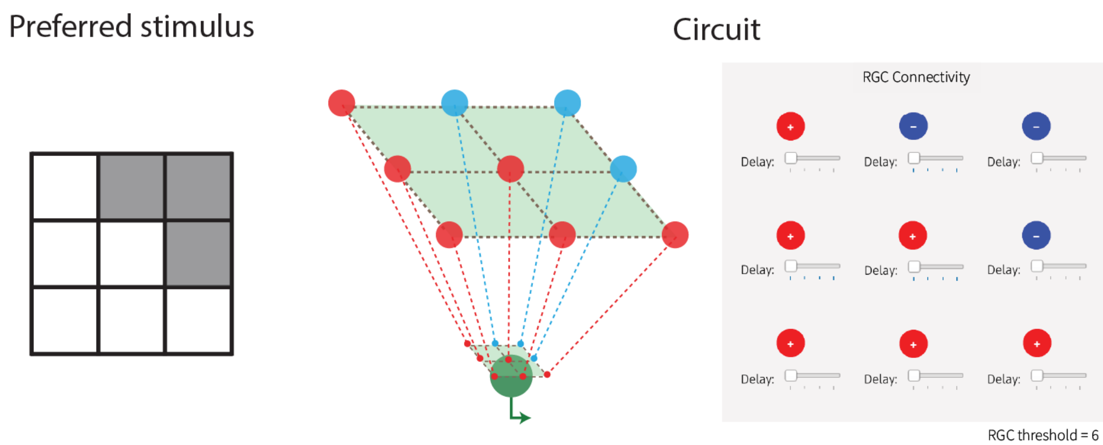


Lesson 4, Medium 6: Preferred stimulus (left) and wiring (right) to Medium 6 mystery circuit

Hard

<u>*Hard 1:* Shape-selective cell (triangle)</u>

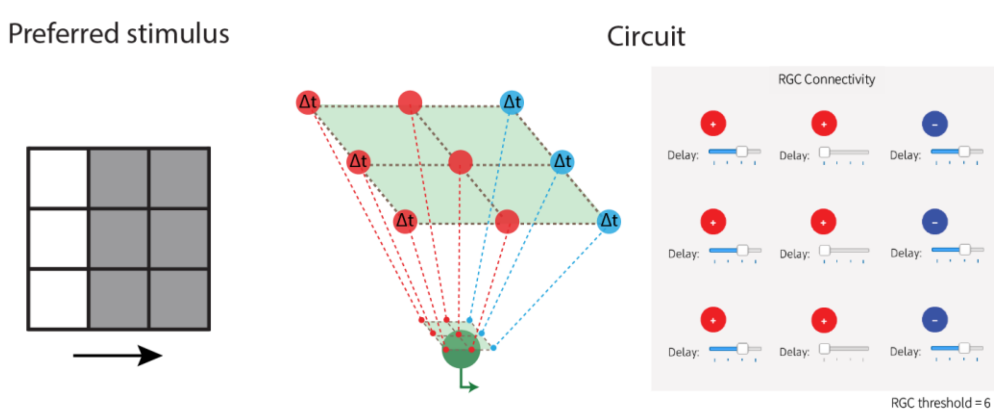
- Preferred stimulus: right-angle in the bottom-left of the receptive field
- Ganglion cell threshold: 6



Lesson 4, Hard 1: Preferred stimulus (left) and wiring (right) to Hard 1 mystery circuit

<u>*Hard 2:* Direction selective cell</u>

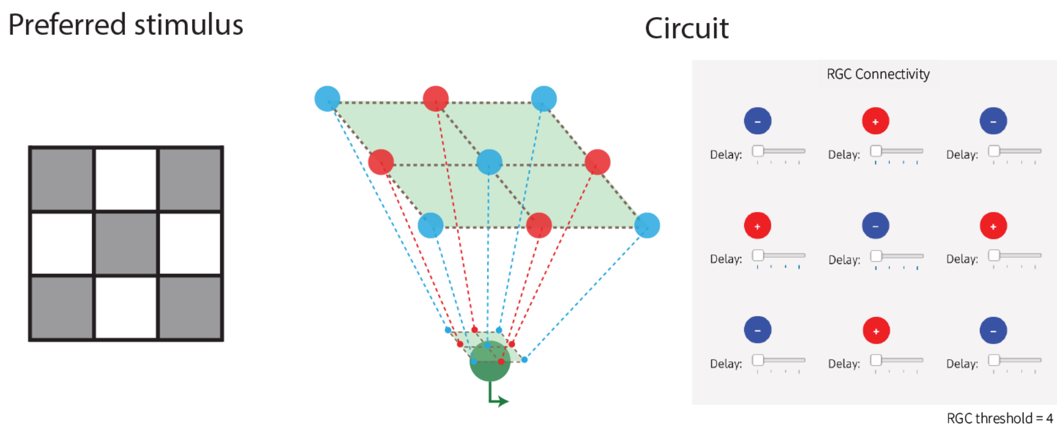
- Preferred stimulus: rightward-moving vertical bar of light
- Photoreceptors in the left and right columns should be configured with medium time delays (please see *Lesson 3, Activity #1 Solution* for a detailed explanation of time-aligned input summation.
- Ganglion cell threshold: 6



*Lesson 4, Hard 2: Preferred stimulus (left) and wiring (right) to Hard 2 mystery circuit. *note, because the speed selectivity of RetINaBox direction selective cells is broad, we accept any time delay input as correct in Discovery mode direction selective challenges.*

Hard 3: Shape (diamond) selective cell

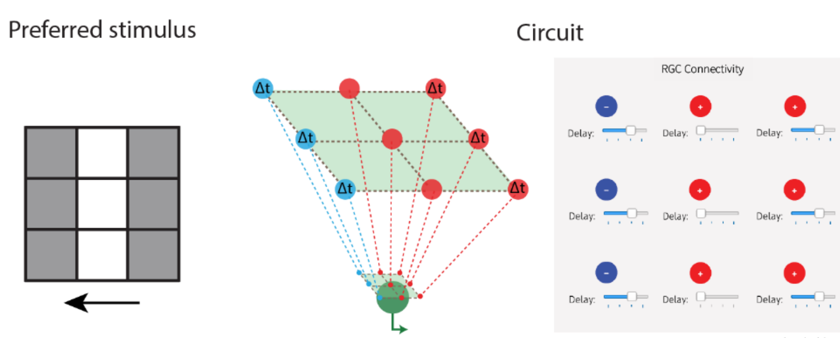
- Preferred stimulus: medium-sized ring of light / diamond (excludes the center)
- Ganglion cell threshold: 4



Lesson 4, Hard 3: Preferred stimulus (left) and wiring (right) to Hard 3 mystery circuit

Hard 4: Direction selective cell

- Preferred stimulus: leftward-moving vertical bar of light
- Photoreceptors in the left and right columns should be configured with a medium time delays (please see *Lesson 3, Activity #3* for a detailed explanation of time-aligned input summation.
- Ganglion cell threshold: 3



*Lesson 4, Hard 4: Preferred stimulus (left) and wiring (right) to Hard 4 Mystery Circuit. *note, because the speed selectivity of RetINaBox direction selective cells is broad, we accept any time delay input as correct in Discovery mode direction selective challenges.*