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, your 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 difference between the inside and outside the cell. 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***—onto ganglion cells, which send retinal signals out of the eye and to the rest of the brain, via the ***optic nerve***.

Within the retina, complex connectivity patterns between bipolar cells, horizontal cells, amacrine cells and ganglion cells transform the photoreceptor-mediated signals (which themselves just signal increases or decreases in luminance) into visual feature detectors. 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 to ganglion cells, via a network of retinal cells. Ganglion cells send integrate these signals and send outputs to the brain for further interpretation.*

However, retinal anatomy is a bit more complex. Photoreceptors (and all the other cell types pictured above) are arranged in a dense, 3D ***mosaic***. Each photoreceptor captures a tiny portion of the visual scene, but together they encode the complete image that you use to navigate the world.

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*

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 that preserves the key principles of visual processing, but as a hands-on tool that you can wire, tweak, and test yourself. RetINaBox contains a 3x3 array of photoreceptors, which directly connect to 2 retinal ganglion cells.

Figure 3. *Circuitry of the simplified model RetINaBox. Light is detected by photoreceptors, which synapse on – or connect to – ganglion cells.*

RetINaBox has a few key components:

- A 3x3 array of light-sensitive ***photodiodes*** (*which* ***model photoreceptors***) that detect changes in infrared light and convert these visual signals into electrical signals that they then send to 2 model retinal ganglion cells.
- Two ***model ganglion cells*** 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 remains unconnected)
- **Temporal delay:** how long the photoreceptor signal takes reach the ganglion cell (this mimics biologically plausible time delays which can be helpful for 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:

1. **Visual Stimulus Controller**: controls the activation of a 3x3 LED array, which allows precise control of which model photoreceptors get activated. You decide which photoreceptors are connected to the ganglion cell (these are the 'selected' neurons in the GUI), which ones are not connected ('unselected' neurons), and 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)

2. **Connectivity Manager**: allows users to connect each model photoreceptor to one (or both) ganglion cell(s), specifying the signal **polarity** (+ or -) and **delay** (short, medium, or long**)**.
3. **Signal Monitor**: displays the output of each photoreceptor and 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 circuits that detect contrast, orientation, and motion - 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 (*beta testing*)**: 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). You can select 'Static' or 'Motion' modes to activate LED stimuli in either 'Static' or 'Motion' modes. Use the 'On/Off' button to toggle LED activation (see Fig 5, left panel).

Figure 6. *Visual Stimulus Controller interface for selecting and activating LEDs in the 3x3 array to generate custom patterns of light stimulation.*

(2) **Manual visual stimulation with the Visual Stimulus Tool (*real-world testing*)**: turn on 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 array and the photoreceptor array to selectively block light from reaching certain photoreceptors. This is the best way to test that your visual circuit respond selectively to specific real-world visual inputs.

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

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 across space. Visual neurons with center-surround receptive fields respond when, within the small part of the visual scene that they see, some part of their receptive field are bright and other parts are 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 an object

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 specific receptive fields – they respond to different parts of the visual field.*

When a neuron is activated, it doesn't just signal that it's seeing its preferred visual feature, but it signals that the feature is within its 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.

Figure 9. *Example: spotting a red apple among green leaves in a tree. If two neurons have receptive fields in different parts of the visual field, the neuron whose receptive field overlaps with the apple's location will respond, allowing the brain to detect and locate exactly where it is, so you can precisely reach for it.*

(2) Estimating the size of an object

Aside from knowing *where* something is in our visual system, 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 by having downstream neurons – such as retinal ganglion cells – integrate signals from multiple neighboring photoreceptors and their adjacent receptive fields. If only a few nearby photoreceptors are activated, the object is likely small; if many are activated across a broader area, the object is likely larger. In this way, our visual system begins to estimate an object's size and its relative distance.

Figure 10. *Example: looking up at the sky and seeing the silhouette of an airplane. If the airplane covers only a small part of the visual field, it's likely far away. If it takes up a large portion, it's probably much closer.*

Lesson 1 Objective

Build and test a simple circuit that mimics a center-surround retinal ganglion cell to explore how the visual system detects spots of light. Beta test your circuit by activating different LEDs ('static' mode). Finally, perform the real-world visual stimulation using the clear plastic board and clay to selectively block light from different LEDs (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. In other words, they fire when a spot of light precisely activates their receptive field center but stay silent if light falls on the surround. If light falls both on center and surround, the response is much weaker than when the center alone was activated.

Use the GUI to build a circuit with a ON-center/OFF-surround ganglion cell that responds only when the center model photoreceptor of the 3x3 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

In Activity #1, you built a circuit with a ganglion cell whose receptive field was located at the center of the photoreceptor array. This cell responded only when the center photoreceptor was activated, and not when any of the surrounding photoreceptors were activated. Your next task is to a ganglion cell with the same size preference (as in Activity #1), but whose receptive field is in a **different position** on the photoreceptor array.

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

Your next task is to wire two different ganglion cells 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 **slightly larger** spot of light.

Challenge: Codebreaking with center surround receptive fields

Now that you've learned how to make ganglion cells that selective 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 **cypher**, which will help you decode the message. The cypher will tell you the visual feature preferences for RetINaBox's two ganglion cells, RGC1 and RGC2. The cypher 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. Wire RetINaBox so that the two ganglion cells respond to the indicated visual stimuli. One important note – you need to make sure that it is possible for both ganglion cells to be activated simultaneously by a single visual stimulus!
2. Present the visual stimuli from the code to RetINaBox and monitor the responses of the ganglion cells
3. For each visual stimulus, use the cypher to translate the GC1/GC2 output into a letter.
4. Repeat for each stimulus and piece together the full secret message.

See the example below:

Challenge #1

**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 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 their receptive field, they are selective to edges or lines of specific lengths and orientations within their receptive fields. In this lesson, you'll explore how ganglion cells in the retina can become selective lines of specific orientations and how you can use these feature detectors to build a shape detector.

Figure 11. *Example: a house might seem like a single, familiar object - but your brain parses it by piecing together many lines and edges of different angles at different locations.*

Objective

Build and test a circuit that mimics an orientation-selective retinal ganglion cell to understand how the visual system combines simple features (i.e., lines of various angles) to recognize complex shapes. Beta test your circuit 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 selectively blocking light from different LEDs. More specifically, allow light to pass through a line of specific orientation (e.g., horizontal, vertical, or diagonal) while blocking out the rest with clay to test your detector (see *How to test your circuits section* for details).

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

Configure a circuit with a ganglion cell that responds only 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. The ganglion cell should not respond to line of the same length but 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 with a ganglion cell that responds to a line of the same thickness as above but only responds when the line is diagonal to the first ganglion cell's preferred stimulus. This second ganglion cell should not respond to a line of any other orientation or thickness, of to a line of a 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 two ganglion cells, that both 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 the lines that activate ganglion cell 1 and ganglion cell 2.

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 manual on page 9. Once you've 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 Figure 12). 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 12. *Circuit wiring of the buzzer. Please See page 9 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. 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 13. *Example: animals like fish and frogs rely on this ability to distinguish potential prey and other fish (left; small moving spots) from predators hunting them (right; large, looming shadows).*

To generate preferences for stimuli moving in specific directions, our visual system takes advantage of the fact that a moving stimuli 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/trailing edges of its receptive field.

Figure 14. *As an object moves across the visual field, different photoreceptors with different 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. Beta test your circuit by activating different combinations of LEDs (use the GUI's 'Motion' mode, and select a speed and direction of motion). Then, perform the real-world visual stimulation using the clear plastic board and clay to selectively block light from different LEDs, and sweeping the stimulus across the photoreceptors (see *How to test your circuits section* for details). Here, you could also try sweeping your hand across RetINaBox as a manual visual stimulus.

The key to direction selectivity lies in asymmetric anatomical connections that differentially process visual stimuli moving in preferred vs. null directions. In RetINaBox, these asymmetric differences can be implemented with **time delays** that can be asymmetrically added to the photoreceptor arrays Connectivity Manager. These delays ensure that inputs only summate (and the ganglion cell fires) when a stimulus moves in the cell's preferred direction.

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

Build a circuit where one ganglion cell responds to a vertical line moving leftwards. Test your circuit by moving a vertical bar of light across your array in both left and right directions.

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

Next, build a second circuit where one ganglion cell responds to a vertical line moving rightwards wards. Test your circuit by moving a vertical bar of light across your array in both right and left directions.

Activity #3: build a slow/fast-moving direction-selective ganglion cell

Build a circuit where one ganglion cell responds to a vertical line slowly moving rightwards, while the second ganglion cell responds to a vertical line moving in the same direction, but more quickly. Test your circuit by moving a vertical bar of light rightwards across your array at various speeds.

Activity #4: build a left-moving direction-selective ganglion cell that responds to different speeds

Finally, build a ganglion cell that responds to a single direction of motion (leftwards), and can do so across a wide range of speeds.

Challenge: Block-breaking with direction-selective circuits

Block Breaker is a classic arcade game where players control a paddle using leftward and rightward motion to bounce a ball and break several rows of bricks. The goal is to clear all the bricks without letting the ball drop. Your next task is to configure two ganglion cells with opposite direction selectivity 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 GC1 is selective *only* for leftward motion and GC2 is selective *only* for rightward motion. You

may choose any temporal delay, but we recommend building each ganglion cell to respond to their specific direction across a **wide range of speeds** for more robust control of the paddle.

- **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! The brick breaker paddle is controlled by your two ganglion cells. Leftward motion (i.e., GC1 activation) should move the paddle leftwards, while rightward motion (i.e., GC2 activation) should move the paddle rightwards.

Figure 15. *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, there are three levels of difficulty (Easy, Medium, Hard), each with their own set of challenges. For each challenge, you'll start with 100 points. To complete the challenge, you'll need to discover (i.e. correctly submit an answer) regarding 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. If you get stuck along the way, you can request hints, but each one will cost you 5 points. Incorrect answers also cost you 5 points. Your goal is to complete each challenge with the highest score possible.

Figure 16 *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? Or a combination of both? Using your **Visual Stimulus Tool** (clear plastic card and modeling clay) to test different stimuli to uncover its preference. 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, some even prefer rotating stimuli!

(2) Discover the Circuit

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!

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.

- In the GUI, connect the center photoreceptor to a ganglion cell with **positive polarity** (excitatory) and no delay (0 ms)

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

- In the GUI, connect each surround photoreceptor to the same ganglion cell with negative polarity (inhibitory), and no delay (0 ms).

Set the ganglion cell's threshold to 1.

This means that 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.

Inputs & wiring to the RGC (center-surround cell)

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 9x9 array for either ganglion cell.

Example solution 1

Inputs to Ganglion Cell: 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. Ganglion cell threshold is set to 1.

Inputs and wiring of the ganglion cell, whose receptive field is in the corner of the array (left).

Example solution 2

Inputs to Ganglion Cell: 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. Ganglion cell threshold is set to 1.

Inputs and wiring of the ganglion cell, whose receptive field is on the edge of the array.

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

Inputs to Ganglion Cell 1 (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 *only* illuminating the center photoreceptor.

Inputs & wiring to RGC1 (small spot detector)

Inputs to Ganglion Cell 2 (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, or to the side) 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.

Inputs & wiring to RGC2 (larger spot detector)

Challenge: Codebreaking with spot detectors

Challenge #1

Inputs to GC 1: 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 ganglion cell threshold is set to 4.

Inputs & wiring to RGC1 (large spot detector with off-center receptive field)

Inputs to GC 2: 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, -). The ganglion cell threshold is set to 1.

Inputs & wiring to RGC2 (spot detector with off-center receptive field)

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

Extra problems

Challenge #2

Inputs to GC 1: This center-surround cell responds only when the top right photoreceptor is activated. This photoreceptor should have positive polarity (red, excitatory, +). All other surround photoreceptors have negative polarity (blue, inhibitory, -). The ganglion cell threshold is set to 1.

Inputs to GC 2: This cell is selective to a 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, -). The ganglion cell threshold is set to 2.

Inputs & wiring to RGC1 (spot detector with off-center receptive field)

Inputs & wiring to RGC2 (vertical line-segment detector)

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

Challenge #3

Inputs to GC 1: This cell is selective to a 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, -). The ganglion cell threshold is set to 2.

Inputs & wiring to RGC1 (vertical line-segment detector)

Inputs to GC 2: This cell is selective to a 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, -). The ganglion cell threshold is set to 2.

Inputs & wiring to RGC2 (horizontal line-segment detector)

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

Challenge #4

Inputs to GC 1: This orientations-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, -). The ganglion cell threshold is set to 3.

Inputs & wiring to RGC1 (orientation-selective cell)

Inputs to GC 2: 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, -). The ganglion cell threshold is set to 1.

Inputs & wiring to RGC2 (spot detector with off-center receptive field)

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

Challenge #5

Inputs to GC 1: 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, -). The ganglion cell threshold is set to 4.

Inputs & wiring to RGC1 (larger spot detector with off-center receptive field)

Inputs to GC 2: 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, -). The ganglion cell threshold is set to 1.

Inputs & wiring to RGC2 (spot detector with off-center receptive field)

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

Challenge #6

Inputs to GC 1: 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, -). The ganglion cell threshold is set to 1.

Inputs & wiring to RGC1 (spot detector with off-center receptive field)

Inputs to GC 2: This orientations-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, -). The ganglion cell threshold is set to 3.

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

Connect 3 adjacent photoreceptors (e.g. a vertical line) to a ganglion cell, so that it fires only when all 3 photoreceptors are activated (i.e., when a vertical bar of light is present)**.**

In the GUI:

- Connect 3 photoreceptors in a straight 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.

Inputs & wiring to RGC1 (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 9x9 array.

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

Connect 3 adjacent photoreceptors along the diagonal to a ganglion cell, so that it fires only when a diagonal bar of light is present**.**

In the GUI:

- 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.

Inputs & wiring to RGC1 (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 surrounding 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.

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.

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.

Ganglion Cell 1 should 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, 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)**.**

Inputs & wiring to RGC1 (vertical *orientation-selective cell)*

Ganglion Cell 2 should 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, 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)**.**

Inputs & wiring to RGC2 (horitontal orientation-selective cell)

For each of the ganglion cells, make sure to silence any photoreceptors that are part of the other ganglion cell's preferred stimulus (grey). This ensures that each ganglion cell responds only to its own preferred orientation, without being suppressed by the other ganglion cell's preferred orientation. Connect the remaining surrounding photoreceptors to the ganglion cell with a negative (inhibitory) polarity. Set each ganglion cell threshold to 3, so that the ganglion cell will *only* fire when all 3 positive photoreceptors are activated in the correct configuration.

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. The circuit will only work properly when the speed of motion matches the timing of the delays, allowing all inputs to summate at the ganglion cell simultaneously.

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

Solution A

The ganglion cell receives input from three full columns of excitatory photoreceptors (positive polarity).

- Left-most photoreceptor column (+): No time delay
- Middle photoreceptor column (+): Short time delay
- Right-most photoreceptor column (+): Medium time delay

*** The following would also work for a slower-moving stimulus: No time delay (right-most column), medium time delay (middle column), long time delay (left-most column)*

Set the **ganglion cell threshold to 9.** This ensures that the cell will only fire when all three columns of photoreceptors (9 photoreceptors in total) are activated in sync, i.e., when the motion direction matches the cell's preferred direction and the timing aligns perfectly (leftwards).

This configuration causes the ganglion cell to fire only when a stimulus moves leftward across the array. The stimulus sequentially activates the leftmost, middle, and then right photoreceptors. The delays are configured so that the signals from all three columns arrive simultaneously at the ganglion cell only if the stimulus moves leftwards, triggering it to fire when it reaches threshold. The inputs will not summate in time if the stimulus does not move in the preferred direction.

Inputs & wiring to RGC1 (left-moving direction-selective cell)

Solution B

Alternatively, the ganglion cell can receive input from two full columns of excitatory photoreceptors (positive polarity) and one full column of inhibitory photoreceptors (negative polarity).

- Left-most photoreceptor column (+): short/medium time delay
- Middle photoreceptor column (+): No time delay
- Right-most photoreceptor column (-): 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 motion direction matches the cell's preferred direction and the timing aligns perfectly (leftwards).

This configuration causes the ganglion cell to fire only when a stimulus moves leftward across the array. The stimulus sequentially activates the leftmost, middle, and then right photoreceptors. The delays are set 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.

Inputs & wiring to RGC1 (left-moving direction-selective cell)

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

Solution A

The ganglion cell receives input from three full columns of excitatory photoreceptors (positive polarity).

- Right-most photoreceptor column (+): No time delay
- Middle photoreceptor column (+): Short time delay
- Left-most photoreceptor column (+): Medium time delay

*** The following would also work for a slower-moving stimulus: No time delay (right-most column), medium time delay (middle column), long time delay (left-most column)*

Set the **ganglion cell threshold to 9.** This ensures that the cell will only fire when all three columns of photoreceptors (9 photoreceptors in total) are activated in sync. Please refer to *Activity #1, Solution* A for a detailed explanation of time-aligned input summation.

Inputs & wiring to RGC1 (right-moving direction-selective cell)

Solution B

Alternatively, the ganglion cell can receive input from two full columns of excitatory photoreceptors (positive polarity) and one full column of inhibitory photoreceptors (negative polarity).

- Left-most photoreceptor column (-): short/medium time delay
- Middle photoreceptor column (+): No time delay
- Right-most photoreceptor column (+): 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 motion direction matches the cell's preferred direction (rightwards) and the timing aligns perfectly. Please refer to *Activity #1, Solution* B for a detailed explanation of time-aligned input summation.

Inputs & wiring to RGC1 (right-moving direction-selective cell)

Activity #3: build a slow/fast-moving direction-selective ganglion cell

The key to solving this problem is the **magnitude of the temporal delays** imposed on the circuits seen in Activity #1 (left-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, i.e., when the motion direction matches the cell's preferred direction (rightwards) and the timing aligns perfectly.

Inputs to GC 1 (slow-moving directions-selective cell):

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

Inputs & wiring to RGC1 (slow right-moving direction-selective cell)

Inputs to GC 2 (fast-moving directions-selective cell):

- Left-most photoreceptor column (+): short time delay
- Middle photoreceptor column (+): no time delay
- Right-most photoreceptor column (-): 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* B for a detailed explanation of time-aligned input summation.

Inputs & wiring to RGC2 (fast right-moving direction-selective cell)

Activity #4: build a left-moving direction-selective ganglion cell that responds to different speeds

To make a direction-selective cell that fires for leftward motion across slow, medium, and fast speeds, the key is to combine temporal delays on different rows of the array, so a moving bar of different speeds will time-align inputs to threshold.

- Left-most photoreceptor column (inhibitory, -)
    - Top row: short time delay
    - Middle row: medium time delay
    - Bottom row: long time delay
- Middle photoreceptor column (excitatory, +): no time delay
- Right-most photoreceptor column (excitatory, +):
    - Top row: short time delay
    - Middle row: medium time delay
    - Bottom row: long time delay

Set the ganglion cell threshold to 4.

Inputs & wiring to RGC2 (left-moving direction-selective cell that responds to different motion speeds)

For slow leftward motion, the excitatory photoreceptor with a long time delay (right column) will align in time with the undelayed middle column, so that all inputs summate to threshold. Similarly, for fast leftward motion, the excitatory photoreceptor with a short time delay (right column) will align in time with the undelayed middle column. Notably, the left inhibitory column carries the same mixed time delay values, providing null-direction suppression across all speed ranges.

Challenge: Block-breaking with direction-selective circuits

The key to solving this problem is the **temporal delays** imposed on the circuits seen in Activity #1 (left-direction selective cell) and Activity #2 (right-direction selective cell). Please refer to the *Solution to Activity #1* for a detailed explanation of time-aligned input summation. To ensure that ganglion cell responses are robust so that the paddle is maximally responsive, each direction-selective cell should respond to slow, medium, or fast motion speeds. As seen in Activity #4, the key is to combine temporal delays on different rows of the array.

Inputs to GC1: 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 4.**

- Left-most photoreceptor column (inhibitory, -)
    - Top row: short time delay
    - Middle row: medium time delay
    - Bottom row: long time delay
- Middle photoreceptor column (excitatory, +): No time delay
- Right-most photoreceptor column (excitatory, +)
    - Top row: short time delay
    - Middle row: medium time delay

    - Bottom row: long time delay
-

Inputs & wiring to RGC1 (left-moving direction-selective cell)

Inputs to GC2: 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 4.**

- Left-most photoreceptor column (excitatory, +)
    - Top row: short time delay
    - Middle row: medium time delay
    - Bottom row: long time delay
- Middle photoreceptor column (excitatory, +): No time delay
- Right-most photoreceptor column (inhibitory, -)
    - Top row: short time delay
    - Middle row: medium time delay
    - Bottom row: long time delay

Inputs & wiring to RGC2 (right-moving direction-selective cell)

Discovery Mode

Easy

Easy 1: Center-surround cell

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

Preferred stimulus

Circuit

Preferred stimulus (left) and wiring (right) to Easy 1 mystery circuit

Easy 2: Orientation-selective cell

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

Preferred stimulus

Circuit

Preferred stimulus (left) and wiring (right) to Easy 2 mystery circuit

Easy 3: Orientation-selective cell

- Preferred stimulus: static horizontal line in the center field

- Ganglion cell threshold: 3

Preferred stimulus (left) and wiring (right) to Easy 3 mystery circuit

Easy 4: Center-surround cell

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

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

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

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

Preferred stimulus (left) and wiring (right) to Easy 7 mystery circuit

Medium

Medium 1: Ring-selective cell

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

Preferred stimulus (left) and wiring (right) to Medium 1 mystery circuit

Medium 2: Shape (T) selective cell

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

Preferred stimulus (left) and wiring (right) to Medium 2 mystery circuit

Medium 3: Shape (X) selective cell

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

Preferred stimulus (left) and wiring (right) to Medium 3 mystery circuit

Medium 4: Shape (+) selective

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

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

Medium 5: Center-surround cell

- Preferred stimulus: Medium-sized spot of light in the center of the receptive field
- Ganglion cell threshold: 4

Preferred stimulus (left) and wiring (right) to Medium 5 mystery circuit

Medium 6: Orientation selective cell

- Preferred stimulus: horizontal line segment in the center-right of the receptive field
- Ganglion cell threshold: 2

Preferred stimulus (left) and wiring (right) to Medium 6 mystery circuit

Hard

Hard 1: Shape-selective cell (triangle)

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

Preferred stimulus (left) and wiring (right) to Hard 1 mystery circuit

Hard 2: Direction selective cell

- Preferred stimulus: rightward-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: 6

Preferred stimulus (left) and wiring (right) to Hard 2 mystery circuit

Hard 3: Shape (diamond) selective cell

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

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 column 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

Preferred stimulus (left) and wiring (right) to Hard 4 Mystery Circuit

Hard 5: Shape-Direction selective cell

- Preferred stimulus: leftward-moving C shape
- Corner photoreceptors 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: 5

Preferred stimulus (left) and wiring (right) to Hard 5 Mystery Circuit