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ARTICLE
NeuroBytes Electronic Neuron Simulators and the 2017 FUN Summer Workshop

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During the 2017 FUN Summer Workshop held at Dominican University, we ran two sessions that allowed participants to build their own neural circuits with NeuroBytes electronic neurons. Here we briefly detail those sessions and discuss further the updates to the NeuroBytes technology since our last article was published in the Spring 2017 issue of *JUNE*.

Key words: FUN Summer Workshop, electronic neurons, simulation, physiology, engineering, curriculum

NeuroBytes are electronic neuron simulators that allow students to learn about the nervous system while building their own neural circuits, synapse by synapse. Each module contains a small microcontroller on which a particular simplified neural cell behavior has been pre-programmed. The neurons have an embedded LED that uses variable luminance and color to indicate the virtual membrane potential of the electronic neuron (Fig. 1).

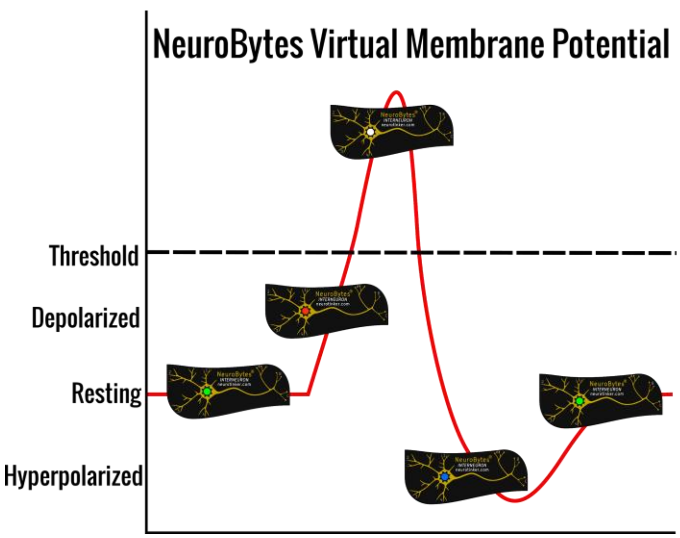

Figure 1. The NeuroBytes LED is used to display the virtual membrane potential changes that take place during the action potential.

Excitatory (red) and inhibitory (blue) neurotransmitter cables are used to connect axon terminal outputs with dendrite inputs, and signals propagated through these cables increase or decrease post-synaptic membrane potential, respectively. Through the use of NeuroBytes Sensory Neurons that detect changes in luminance or touch, NeuroBytes Integration neurons that combine and process sensory signals in similar ways as neurons in the central nervous system, and NeuroBytes Motor Neurons that connect to servo motors to turn sensation and integration into motion, students can physically build simple or complex electronic neural circuits that respond to their environment in interesting and unique ways (Fig. 2).

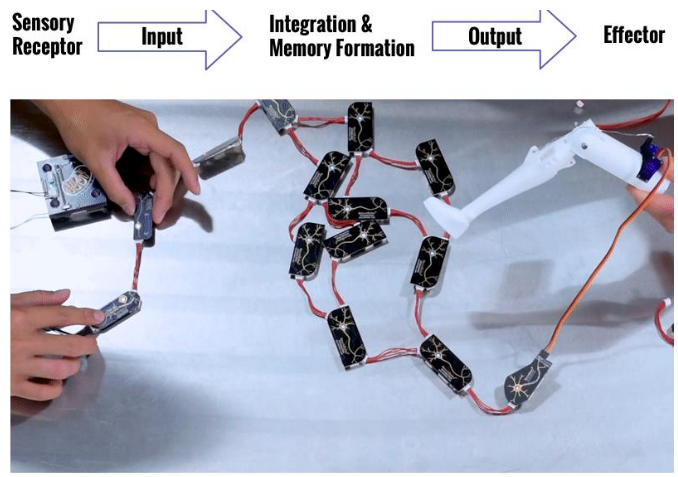

Figure 2. NeuroBytes electronic neurons can be constructed into networks that sense the environment, process and integrate that sensation, and produce motion.

We have previously reported the results of NeuroBytes prototype integration into an undergraduate anatomy and physiology course (Petto et al., 2017). Here we discuss the progress made in the interim with updated and new modules, some of which were used during the NeuroBytes sessions in the 2017 FUN Summer Workshop held at Dominican University (Fig. 3).

Figure 3. NeuroBytes session participants from the 2017 FUN Summer Workshop at Dominican University.

The NeuroBytes ecosystem is broken up into three categories: Sensory Neurons, Integration Neurons, and Motor Neurons (Fig. 4).

SENSORY NEURONS

There are currently three different types of NeuroBytes specialized for sensing the environment. All three of these can send outputs via excitatory or inhibitory neurotransmitter cables to Integration or Motor neurons.

Touch Sensory Neurons (Fig. 4F) simulate sensory neurons with free nerve endings in the skin that are sensitive to crude touch. There is a switch on the front of the module that, when clicked, always produces action potentials in the neuron. These modules do not show sensory adaptation.

Pressure Sensory Neurons (Fig. 4E) simulate sensory neurons with Pacinian corpuscle encapsulated endings in the skin that are sensitive to pressure. There is an embedded force sensitive resistor that works much like physiological Pacinian corpuscles. A light touch produces subthreshold depolarizations in the module. As the touch becomes more intense, action potentials are produced at a steady rate. Increasing pressure leads to action potentials generated at a higher frequency, in line with the concept of rate coding in physiological sensory neurons. With sustained pressure, these modules will show adaptation, again similar to the behavior of physiological pressure sensitive neurons.

Rod Photoreceptors (Fig. 4B) simulate rods in the physiological retina. These modules respond to changes in luminescence detected through a light sensor embedded into the distal portion of the module, where the light sensitive disks are found in physiological rods. NeuroBytes rods also contain two buttons unique to this module that are used to set the minimum and maximum light levels that the simulator should respond to. Unlike physiological rods that increase their output in the dark, these modules have both "Light" and "Dark" output connectors. These allow the user to connect excitatory or inhibitory neurotransmitter cables and build circuits that can model the retina, but also provide for maximal flexibility when designing new light-driven circuits unconstrained by normal physiology.

Interneurons (Fig. 4C) are the primary means by which Sensory Neuron signals are integrated and processed in NeuroBytes circuits. These modules have two long and two short dendrites programmed with different input weightings. Signals coming into the short dendrites are given a higher weighting than those coming into the long dendrites, which allows for modeling of the length constant and spatial summation. Repeated input signals from the same dendrite can also build upon each other, allowing experimentation with temporal summation. Interneurons also contain a "Potentiation Mode" which allows the user to experiment with the concepts of cooperativity, specificity, and associativity.

Tonically Active Neurons (Fig. 4D) are unique to the NeuroBytes ecosystem in that they can fire action potentials without any exogenous input. There is a touch slider on the front of these modules that can be used to set the membrane potential anywhere from a hyperpolarized to a suprathreshold level.

EFFECTOR NEUROBYTES

Motor Neurons (Fig. 4G) have three dendrites of equal weighting for gathering sensory and integrated signals. To allow for maximal flexibility when constructing wheeled vehicles and models of coordinated, antagonistic muscle

Figure 4. The NeuroBytes Neuron Simulator Ecosystem. (*A*) Battery pack. (*B*) Rod Photoreceptor. (*C*) Interneuron. (*D*) Tonically Active Neuron. (*E*) Pressure Sensory Neuron. (*F*) Touch Sensory Neuron. (*G*) Motor Neuron.

action around a joint, Motor Neurons respond uniquely to inhibitory neurotransmitter input. Instead of simply hyperpolarizing to such input, inhibitory input leads to a counter-clockwise rotation of connected servo motors, and the Motor Neuron LED flashes blue to indicate such activity. When Motor Neurons receive excitatory neurotransmitter input, they rotate connected motors in a clockwise direction, and the LED flashes red to indicate this. These modules can control both continuous rotation (wheeled vehicle) and non-continuous rotation (skeletal muscle modeling) servo motors.

KITS

NeuroBytes are packaged together into kits with experiments and curricula that make it easier to implement hands-on neurophysiology learning into the secondary and undergraduate education classroom. All of the kits encourage the users to incorporate artistic design into their neuroscience and engineering constructions. The Skin (Fig. 5D) and Eye (Fig. 5E) Kits incorporate papercraft models specially designed for NeuroTinker by noted STEAM educator Ellen McHenry, of Brain Cap fame (http://ellenjmchenry.com/brain-hemisphere-hat/). These kits encourage users to experiment with physiological as well as novel user-defined circuit behaviors of the sensory nervous system. The Knee-Jerk Reflex Kit (Fig. 5B) allows users to build this reflex from laser cut plywood, held together by rubber ligaments, and set into motion by NeuroBytes and servo motors that simulate the reflex loop and muscles involved in this classic reflex response. The NeuroBuggy Kit (Fig. 5A) allows students interested in the intersection of neuroscience, physiology, and engineering to experiment with vehicles powered by synthetic neural circuits and was based in part on the work of synthetic psychologist Valentino Braitenberg and his book "Vehicles: Experiments in Synthetic Psychology" (Braitenberg, 1984).

The Advanced Network Interface Device (NID) Kit (Fig. 5C) is unique in that it allows for more advanced electrophysiological experimentation. Using the NID hardware box and the companion app, any connected NeuroBytes can be identified virtually on the device screen and its settings adjusted. This is particularly valuable with larger networks (for instance) in which multiple rod photoreceptors need to be calibrated for the room light, or when the memory mode functionality needs to be altered for numerous Interneurons. This kit also utilizes an oscilloscope app which allows for detailed membrane potential visualization and data logging of any of the connected NeuroBytes. Future iterations of the NID interface will also allow for manipulation of individual NeuroBytes dynamics, such as virtual membrane potential level and dendrite and axon terminal weighting.

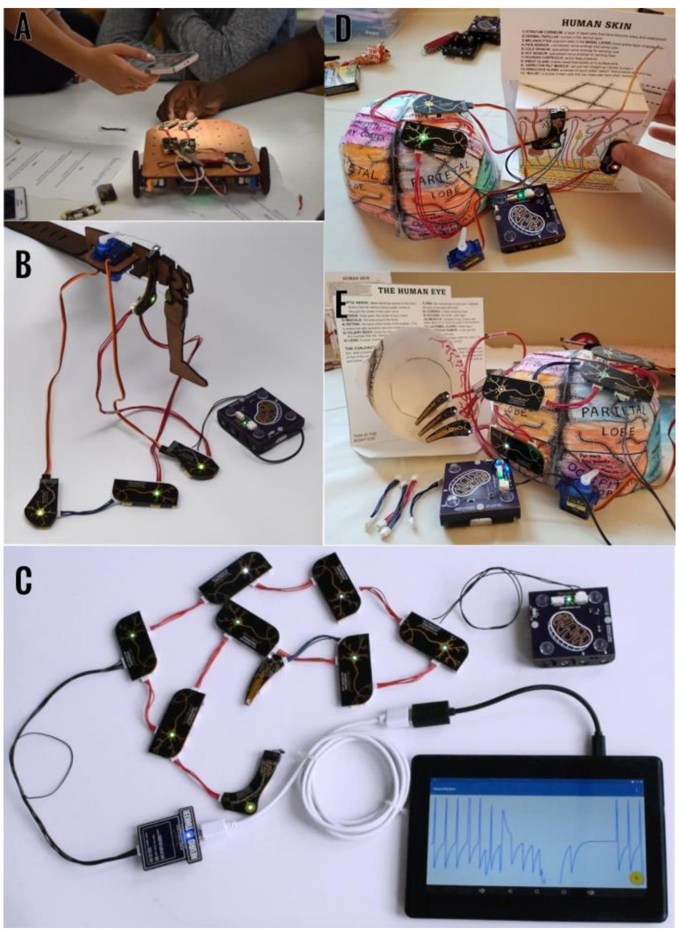

Figure 5. NeuroBytes Kits. (*A*) NeuroBuggy Kit, (*B*) Skin Kit, (*C*) Advanced Network Interface Device Kit, (*D*) Eye Kit, (*E*) Knee-Jerk Reflex Kit.

EXPERIMENTS AND CURRICULA

With support from a Research Experience for Teachers supplement from the National Science Foundation, we have partnered with engineering and life science educators to create experiments and curricula that are freely available on the NeuroTinker website (www.neurotinker.com) and are designed to accompany NeuroBytes neuron simulators. These experiments are in text and video format (Fig. 6), and explore basics of how the various NeuroBytes function, how they can be constructed into functional circuits, and how those circuits can be used to model physiology, as well as extended into the realm of neuroengineering.

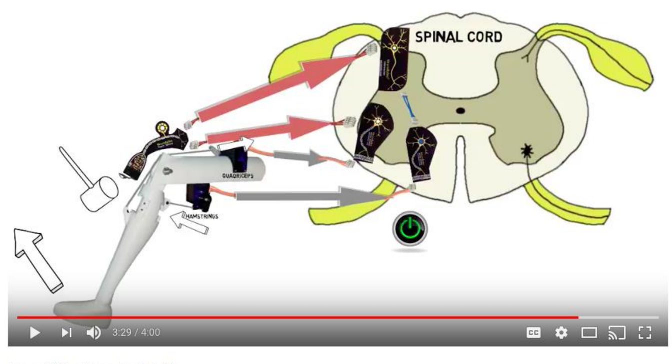

Figure 6. A screenshot from the NeuroBytes video experiment series.

In addition, we have used the educational software tool EDPuzzle (www.edpuzzle.com) to add formative assessment to these video experiments (Fig. 7). This website is free to use for educators and students. Educators can add multiple choice, fill in the blank, or free response questions for students to view and work on in a flipped or traditional course setting. During the FUN Workshop, we asked participants to provide feedback about the NeuroBytes and the utility of using them in their courses. A sampling of their comments:

"Great potential"

"Very cool - excited about them coming out!"

"Had a lot of fun playing with the equipment and can very easily see building NeuroBytes modules into my lab course and upper level seminars."

"I can't wait to incorporate this!"

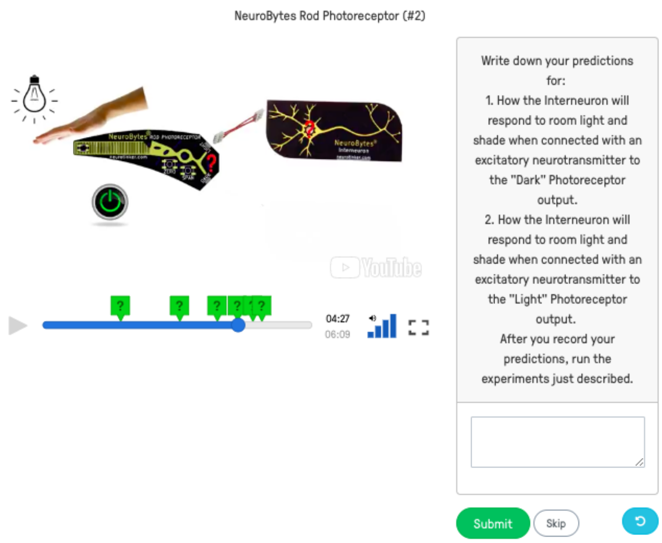

Figure 7. NeuroBytes-based formative assessment. We have adapted selected video experiments to include formative assessment using the EdPuzzle website educational tools.

FUTURE DIRECTIONS

We have recently successfully completed a Kickstarter crowdfunding campaign which has allowed us to capitalize our first manufacturing run of the NeuroBytes modules described herein. With support from our NSF SBIR grant, we are also continuing our research and development efforts on new NeuroBytes modules and behaviors, including an inner ear simulation consisting of vestibular and cochlear modules, cone photoreceptors NeuroBytes, and several other simulations of interest to the neurophysiology and engineering education world. NeuroBytes have been or are currently being used in several undergraduate neuroscience classrooms, and we are developing our undergraduate curricula based on these integration experiences. We are also actively working on integrating our synthetic neural circuits with signals from real nervous systems, recorded by hardware products from our colleagues and friends at Open BCI and Backyard Brains, for example. Since our hardware design files, neuron firmware, and experimentation are all open source, we encourage others to do the same with our technology (with proper attribution) and would welcome collaborations from the neurotechnology and neuroscience education world.

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