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Feature

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Brains–Computers–Machines: Neural Engineering in Science Classrooms

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WHY NEURAL ENGINEERING IN THE SCIENCE CLASSROOM?

Secondary science teachers are challenged to align their curricula to state and national standards while also engaging students' interests and leveraging their everyday experiences through equitable learning opportunities. As the Next Generation Science Standards (NGSS) are being implemented for many states across the nation, science teachers are being required to infuse their curriculum with engineering design challenges built upon contemporary and not just settled science content (NGSS Lead States, 2013; Van Horne and Bell, 2014). In addition, a focus on the three dimensions of science learning (disciplinary core ideas, and cross-cutting concepts and practices) asks teachers to design learning activities that expose students to the practices of professional scientists and engineers so that they deeply engage in *doing* as well as *learning about* science and engineering. Both the NGSS and the Common Core State Standards require teachers to emphasize the cross-disciplinary links between science, technology, engineering, and math (STEM) and English language arts (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010). Emerging, interdisciplinary STEM fields, such as neural engineering, apply cutting-edge scientific knowledge to the design of engineered systems and can help secondary science teachers meet the challenges of this new vision for science and engineering education (National Research Council, 2012).

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With its roots in neuroscience, robotics, and engineering, the field of neural engineering is of high interest to many students. Neural engineering brings together brains, computers, and machines with impressive emerging technologies and has an undeniable "wow" factor. Moreover, many students may already be engaged with gaming, programming, and robotics through school classes and clubs, out-of-school time programs, and personal hobbies. Therefore, by bringing neural engineering topics and related design challenges into the classroom, teachers have the ability to leverage students' interests and to connect their identities inside and outside of the school day. By integrating a study of neuroethics with neural engineering, students can engage in deep discussions about the ethical implications of these new technologies and develop an understanding of the influences of science, engineering, and technology on individuals and society (NGSS Lead States, 2013).

The field of neural engineering aims to design solutions for people with disabilities, disorders, and injuries that affect the nervous system. Neurological disorders likely touch the lives of every student, directly or indirectly, demonstrating the topic's personal relevance and society's need for these new technologies. The World Health Organization (2006) estimates that more than one billion people worldwide are affected by neurological disorders. In the United States, almost 800,000 people experience a stroke (one stroke every 40 s); stroke is also responsible for one of every 20 deaths (one death every 4 min; Mozaffarian, 2015). Traumatic brain injury affects 1.7 million people each year and causes 52,000 deaths (30.5% of all injury-related deaths in the United States) and 275,000 hospitalizations (Faul *et al*., 2010). Particularly relevant to precollege students is the estimated 300,000 sports-related traumatic brain injuries that occur annually, making sports the second most common cause of concussions in Americans 15–24 yr old (Marar *et al*., 2012). Most students will likely know someone with damage or disease of the nervous system because of the high prevalence of stroke and traumatic brain injury and other disorders such as spinal cord injury, Parkinson's disease, Alzheimer's disease, and amyotrophic lateral sclerosis.

Although significant progress has been made in treating many of these disorders, effective therapies are still lacking for conditions such as traumatic brain injury, stroke, and spinal cord damage. Investigators in the relatively new field of neural engineering (neuroengineering) seek innovative treatments and therapies for neurological disorders by bridging the domains of clinical medicine, biology, computer science, materials science, engineering, and neuroscience.

Neural engineering is highly relevant to precollege students. Secondary science teachers can implement engaging curricula and activities to meet the challenges of the new vision for science and engineering education while also motivating their students to consider STEM careers. Neuroscience websites for students and teachers have been reviewed in a previous *WWW.Life Sciences Education Feature* (Chudler and Bergsman, 2014) and will not be discussed here. Rather, this *Feature* focuses on resources about neural engineering that can be used by precollege educators and students, as well as scientists and engineers who engage with the public. The materials reviewed begin with a general introduction to neural engineering that is followed by topics that align with disciplinary core ideas across life sciences, physical sciences, computer science, and engineering.

TEACHING RESOURCES

Introducing Neural Engineering

The Center for Sensorimotor Neural Engineering (www.csne-erc.org), a National Science Foundation (NSF)-funded Engineering Research Center, provides a website with two blogs about recent developments and careers in neural engineering as well as lesson plans and activities for the classroom: *Engage and Enable* (www.csne-erc.org/csne-blogs/engage-enable) and *BrainTech Journal* (www.csne-erc.org/csne-blogs/braintech-journal). The site also includes a glossary of terms related to the field of neural engineering (www.csne-erc.org/sites/default/files/Glossary%20of%20NE%20Terms_K-12%20v2.pdf) and a growing library of teacher-authored curriculum units designed to introduce secondary science students to core concepts in neural engineering (www.csne-erc.org/content/lesson-plans). These materials should provide students and teachers with a basic understanding of the field and can be used to launch a deeper exploration into neural engineering. In addition, *Frontiers for Young Minds* (kids.frontiersin.org/article/10.3389/frym.2013.00007) provides a student-friendly article to introduce the concept of brain–machine and brain–computer interfaces, a fundamental technology within the field (Figure 1).

Complex Systems and Neural Networks

The study of complex systems provides a way for teachers to bridge traditionally distinct subjects across the natural and social sciences, to make the NGSS cross-cutting concept of systems and systems models explicit, and to help students form a "new type of scientific literacy" (Jacobsen, 2001). A focus on neural networks provides an opportunity for precollege students to learn about complex systems while developing knowledge that is foundational to the field of neural engineering. The construction of devices that interface with the nervous system requires knowledge of how neurons code information to and from the brain. For example, to build a brain–computer interface (BCI), investigators must measure and decode the electrical signals of the brain. These signals can then be used to control an external device, such as a computer, motor, or prosthetic limb. A BCI can also use signals from the device to communicate to the brain. Some neural engineers model neural networks to better understand these processes.

"It's a Connected World: The Beauty of Network Science" (www.teachengineering.org/view_curricularunit.php?url=collection/jhu_/curricular_units/jhu_cnetworks_unit.xml) is a two-lesson unit from Johns Hopkins University for students in grades 7–10. The curriculum introduces students to complex networks and graphical representations, including neural networks.

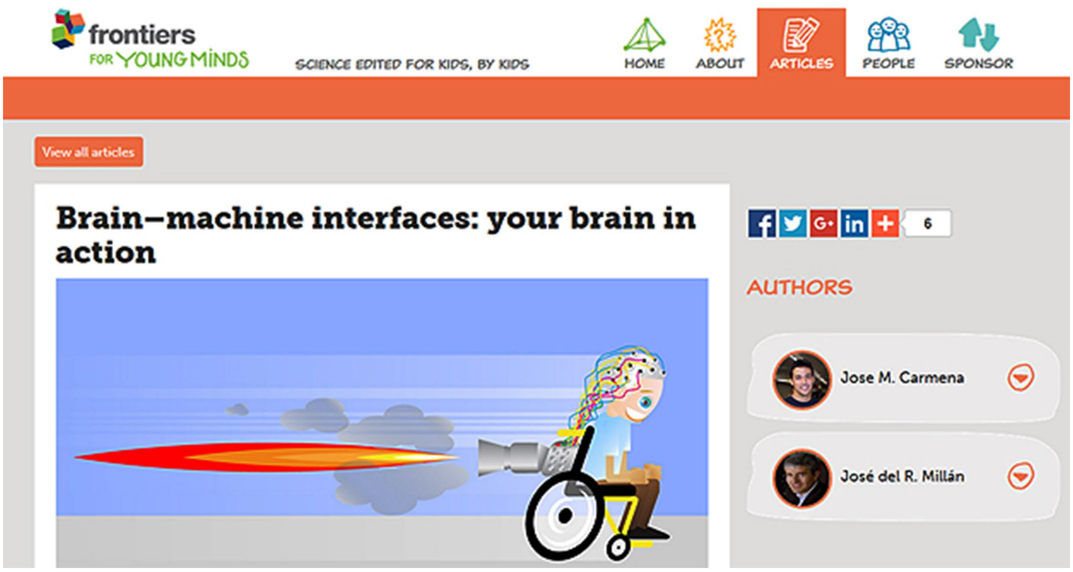

Figure 1. The "Brain-Machine Interfaces" article from *Frontiers for Young Minds* (kids.frontiersin.org/article/10.3389/frym.2013.v00007) provides a student-friendly background about brain–machine and brain–computer interfaces. This screenshot image is courtesy of *Frontiers for Young Minds*.

Biosignals

The nervous system communicates with the rest of the body through chemical and electrical signals. Neural engineers are able to use the electrical signals generated by a person's muscles or brain to control an external device. The electromyogram (EMG; electrical activity recorded from muscles), the electroencephalogram (EEG; electrical brain activity recorded from the top of the scalp), and the electrocorticogram (ECoG; electrical brain activity recorded from the top of the brain) can all be used as control signals. The EEG and ECoG record the activity of thousands of neurons at the same time. Using small implantable electrodes, investigators can record from single nerve cells and use action potentials to control devices. For example, these signals can be used to move cursors on a computer monitor or to drive motors in a robotic prosthetic limb.

Backyard Brains (https://backyardbrains.com/experiments) sells affordable experiment kits and provides free lesson plans for exploring concepts in neuroscience, electrophysiology, neuroprosthetics, and other neurotechnologies (Figure 2). By using Backyard Brains' bioamplifiers with free software and lesson plans, students can record action potentials from a cockroach leg nerve or earthworm ventral cord and measure the EMG activity from their own muscles. This equipment can be combined with Arduino UNO microcontroller boards, sensors, and computers to create novel neural engineering devices such as an EMG-controlled robotic gripper and even a human-to-human interface.

Sensors

Sensors can be used to detect different types of external stimuli (e.g., light, touch, sound, temperature, chemicals, and pressure) in the environment. For neural engineering applications, these forms of stimuli can be converted into electrical signals and directed into the nervous system. Sensors that interact with the nervous system can provide feedback to the brain about the location of a prosthetic arm or can convert sound waves to electrical signals in a cochlear implant to stimulate the auditory nerve. The Computational Neurobiology Center in the College of Engineering at the University of Missouri has created "How Do Sensors Work?," a six-lesson unit for students in grades 4–8 that focuses on the function of human and robotic sensors from an engineering perspective. These materials connect to neural engineering concepts by using LEGO MINDSTORMS NXT robots in a design challenge (www.teachengineering.org/view_curricularunit.php?url=collection/umo_/curricular_units/umo_sensorswork/umo_sensorswork_unit.xml).

Neuroprosthetics

Many neural engineers develop devices to restore or enhance sensory or motor function. These neuroprosthetic devices improve sensory input into the nervous system or motor output from the nervous system. Sensory neuroprosthetics include devices such as cochlear implants for people with hearing impairments and retinal implants for people with visual impairments. A robotic limb is an example of a motor neuroprosthetic. Deep brain stimulation is an example of a neuroprosthetic used in a therapeutic capacity to relieve the symptoms of several neurological disorders.

Prosthetic Limbs. Some neuroprosthetic limbs (also called bionic limbs or smart prosthetics) use BCI technology to move a robotic arm simply by thinking about moving the arm. The amazing power of this technology can be introduced to students through the stories of engineers, physicians and patients profiled in "Harnessing the Power of the Brain," a *60 Minutes* episode (www.cbsnews.com/news/harnessing-the-power-of-the-brain; requires a 99-cent monthly registration fee to view) or through Brown University's BrainGate channel on YouTube (www.youtube.com/playlist?list=PL789FA64D163DF6D0).

The most effective neuroprosthetic limb would send control signals to a device and would also receive sensory signals (i.e., pressure, temperature, or body position awareness) from the device to make adjustments, creating a closed-loop system. TechXcite, from the Pratt School of Engineering at Duke University, has developed a "Bionic Arm" curriculum module for middle school students (techxcite.pratt.duke.edu/curriculum/biomed-arm.php). This unit integrates concepts from electrical, mechanical, and biomedical engineering, and includes both motor and sensory components. Prosthetics that send and receive signals are also the subject of articles and multimedia resources from *Popular Mechanics* (www.popularmechanics.com/science/health/prosthetics/smart-bionic-limbs-are-reengineering-the-human-9160299).

Cochlear Implants. One of the most common neuroprosthetics is the cochlear implant, an electronic device for people with significant hearing loss (sensorineural hearing loss). A cochlear implant bypasses damaged hair cells in the cochlea of the inner ear. It consists of an external microphone, speech processor, and transmitter that work together to send electronic signals about sound to an implanted receiver and electrodes. KidsHealth (kidshealth.org/parent/general/eyes/cochlear.html), the National Institute on Deafness and Other Communication Disorders (www.nidcd.nih.gov/health/hearing/pages/coch.aspx), and the Food and Drug Administration (FDA; www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/ImplantsandProsthetics/CochlearImplants/ucm062823.htm) offer easy-to-read descriptions of cochlear implants. Students who want more in-depth information about cochlear implants can turn to an online resource list titled *Cochlear Implants: Navigating a Forest of Information … One Tree at a Time* (www.gallaudet.edu/Documents/Clerc/NavigatingAForest-Resources.pdf) by Debra Berlin Nussbaum (Cochlear Implant Education Center, Laurent Clerc National Deaf Education Center).

Several online simulators help students experience the impact of cochlear implants. First, students begin by exploring the effects of hearing loss. Hearing Like Me (www.hearinglikeme.com/hearing-loss-simulator-understanding-mild-and-moderate-hearing-loss) and the Hear the World Foundation (www.hear-the-world.com/en/hearing-and-hearing-loss/hearing-loss-what-it-sounds-like.html) have created online simulations in which users choose from different conversations or soundscapes to understand what a person with mild, moderate, or severe hearing loss would experience. Next, students explore an online simulation of what it may be like to hear speech and music with a cochlear implant. The *Cochlear Implant Audio Demos* (developed by Philipos C. Loizou based on work from the University of

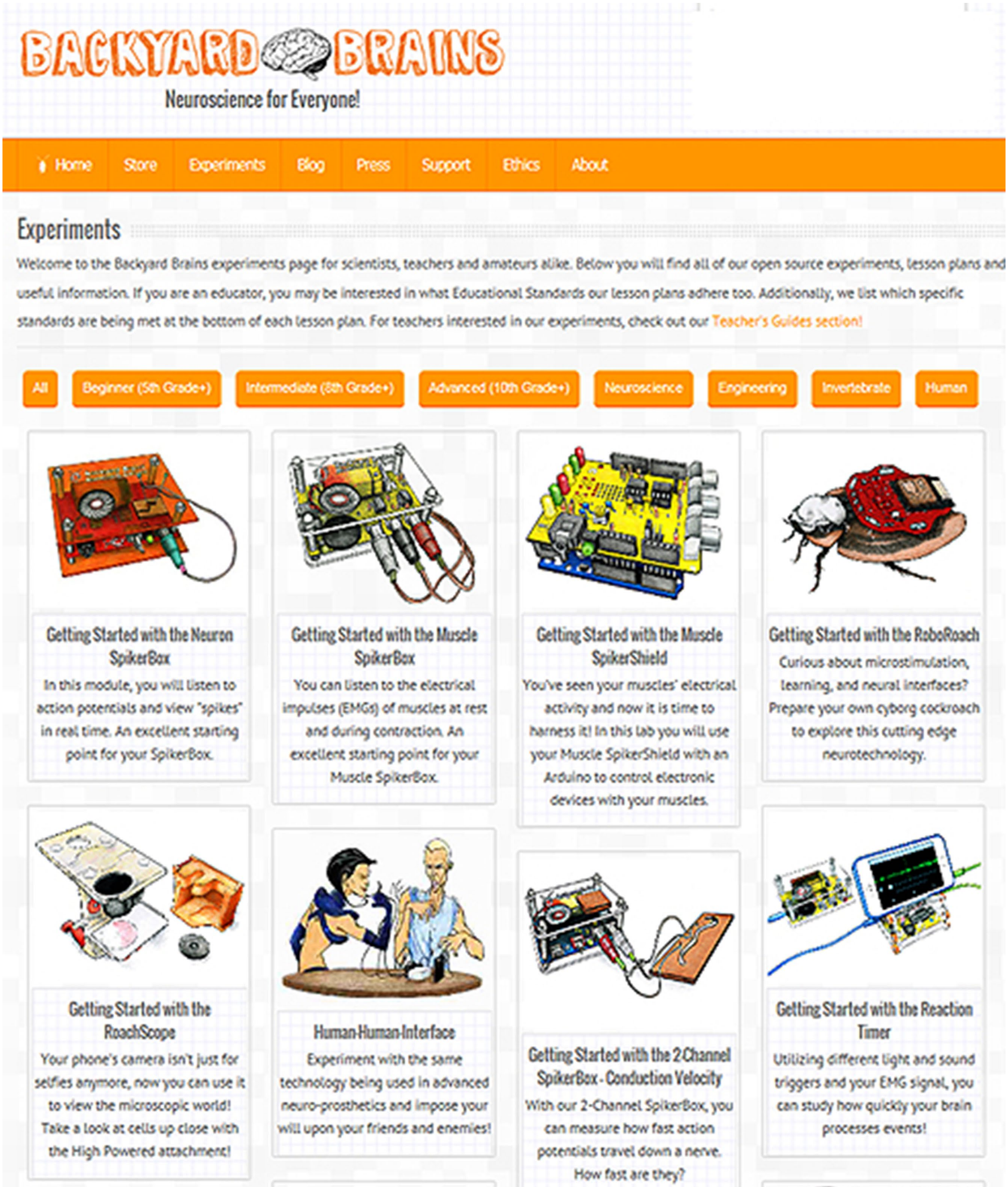

Figure 2. Backyard Brains (https://backyardbrains.com/experiments) sells bioamplifers and offers free lesson plans to explore concepts of electrophysiology, neuroscience, neuroprosthetics, and neural engineering. This screenshot image is used with permission of Backyard Brains.

Texas–Dallas; ecs.utdallas.edu/loizou/cimplants/cdemos.htm) allows listeners to explore the effects of the number of channels and depth of electrode insertion on the clarity of human speech processed by the implant. Audio files can be downloaded from "Sound through a Cochlear Implant" (Action on Hearing Loss; www.actiononhearingloss.org.uk/your-hearing/about-deafness-and-hearing-loss/cochlear-implants/sound-through-a-cochlear-implant.aspx) to compare simulations of speech and music from early and modern cochlear implants.

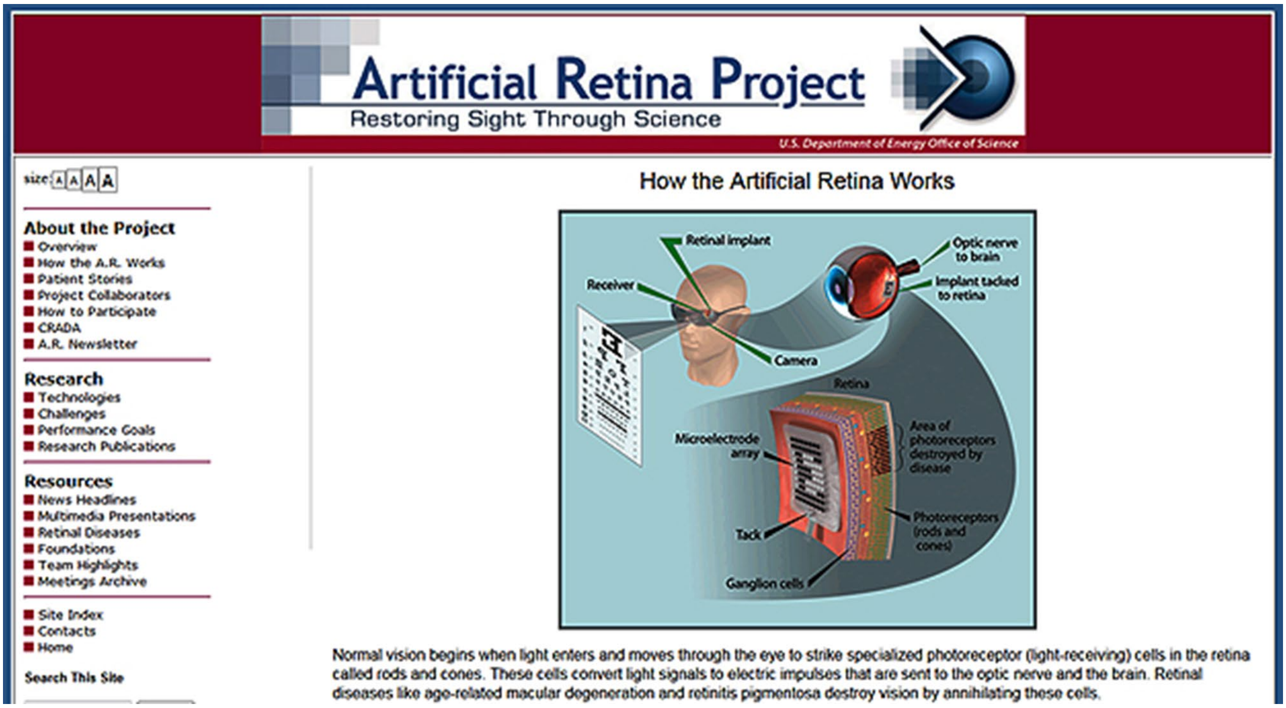

Figure 3. The Artificial Retina Project (artificialretina.energy.gov/howartificialretinaworks.shtml) from the U.S. Department of Energy's Office of Science explains how retinal implants work and their impact on the lives of people who have received them. This image is considered to be in the public domain. Credit: U.S. Department of Energy.

Cochlear implants are controversial, because some people believe that cochlear implants are an affront to the Deaf community and their culture. The Centers for Disease Control and Prevention's Science Ambassador program engages students in a debate about the ethical issues surrounding cochlear implants with a teacher-authored lesson for middle school students titled "Cochlear Implants: The Complex Debate" (www.cdc.gov/excite/ScienceAmbassador/ambassador_pgm/lessonplans_hi.htm).

Retinal Implants. Just 3 yr ago, the FDA approved retinal implants for humans (www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/DeviceApprovalsandClearances/Recently-ApprovedDevices/ucm343162.htm). This device, the Argus II Retinal Prosthesis System by Second Sight, is for people with advanced retinitis pigmentosa. To better demonstrate how a retinal implant helps restore vision, the U.S. Department of Energy has created the Artificial Retina Project website with articles, patient stories, and multimedia presentations that will help students understand the mechanics and impacts of a retinal prosthesis (artificialretina.energy.gov/howartificialretinaworks.shtml; Figure 3). *The Scientist* (www.the-scientist.com/?articles.view/articleNo/41052/title/The-Bionic-Eye) provides a series of short articles in "The Bionic Eye" that provide a general overview about retinal implant devices. To help students understand eye problems, vision deficiencies, and the use of retinal implants, the Integrated Teaching and Learning Program at the College of Engineering, University of Colorado–Boulder authored the "Biomedical Devices for the Eyes" lesson plan for middle school students (www.teachengineering.org/view_lesson.php?url=collection/cub_/lessons/cub_biomed/cub_biomed_lesson07.xml).

Deep Brain Stimulation. Deep brain stimulation (DBS) was pioneered as a treatment to control the symptoms of Parkinson's disease but is now also used to treat people with depression, obsessive–compulsive disorder, dystonia, essential tremor, and pain. Patients undergoing DBS therapy have metal electrodes implanted into specific areas of their brains. The electrodes are attached by wires to an electrical stimulator under the skin in the chest. The stimulator is set to deliver electrical pulses that alter the neural activity of the brain region near the tip of the electrode. Medtronic was an early innovator in the field of DBS for movement disorders and offers a variety of educational tools about DBS therapy on their company website (www.medtronic.com/innovation/smarter-dbs.html). The Medtronic videos of patients before and after DBS surgery are especially helpful in understanding the potential benefits of this therapy. *Deep Brain Stimulation Surgery* is an immersive animated application created by Edheads that invites students to perform all stages of a virtual DBS surgery on a patient with a movement disorder (www.edheads.org/activities/brain_stimulation). The simulation is intended for students in grades 7–12 and includes a teacher guide (Figure 4). Warning: some of the illustrations and photos of actual brain surgery are quite graphic.

Neuroethics. Each new neurotechnological invention has ethical implications, some of which have never been explored previously. Any technology that interfaces with a person's sensory or motor functions can potentially affect that person's ability to process information from the outside world and respond to external stimuli. Mood, cognition, and thought processes may also be altered by devices attached to or implanted into the brain. Moreover, if the brain and device communicate wirelessly, the security of

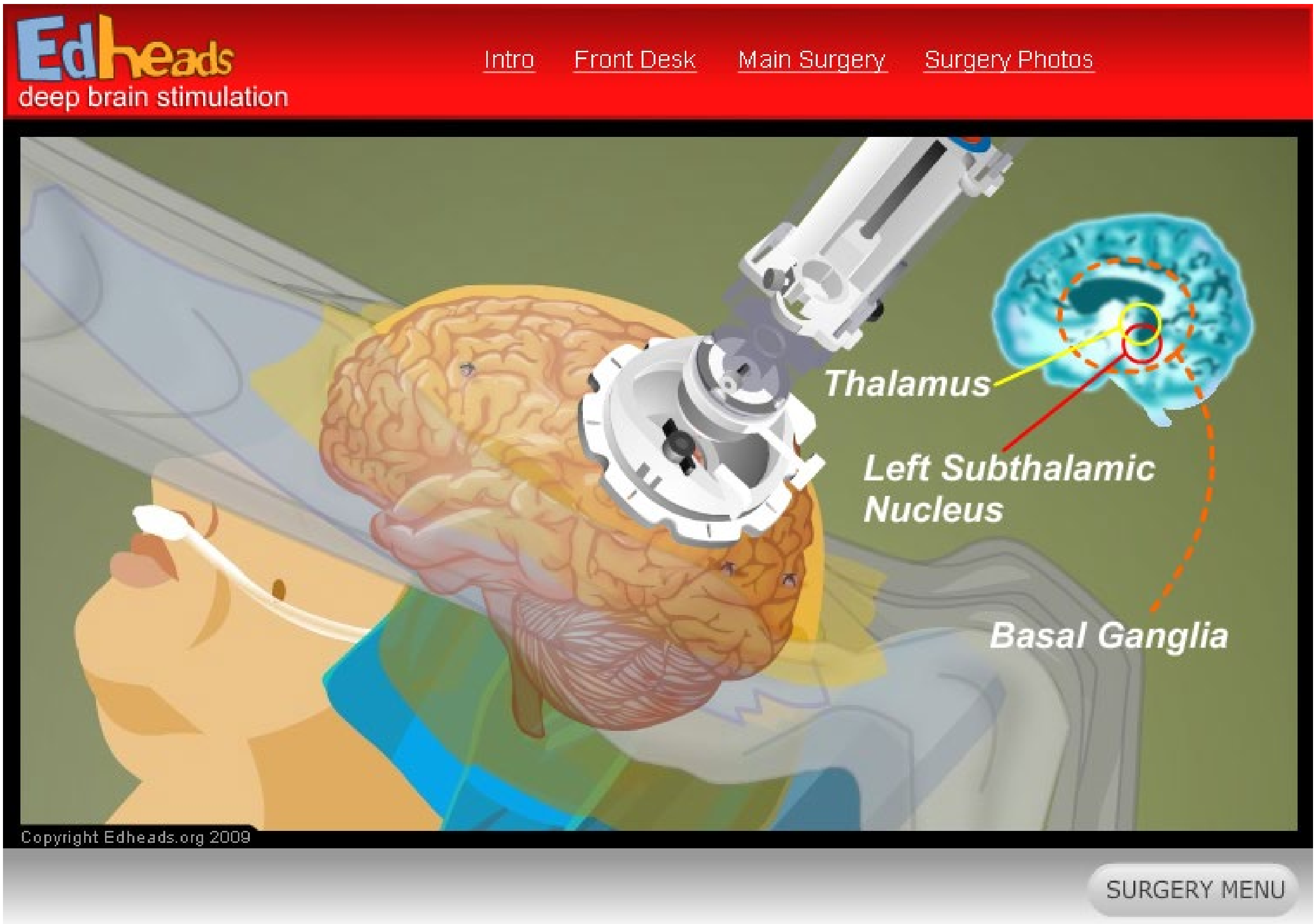

Figure 4. The *Deep Brain Stimulation Surgery* online simulation from Edheads (www.edheads.org/activities/brain_stimulation) allows students to engage virtually in all stages of brain surgery to place and test an electrode for deep brain stimulation therapy. This screenshot image is courtesy of Edheads.

the input and output signals may be at risk from hackers. High school students can explore these topics through Neuroethics: Implications of Advances in Neuroscience, an online course from the Center for Bioethics at the College of Physicians and Surgeons of Columbia University (ccnmtl.columbia.edu/projects/neuroethics/index.html). The course covers the neuroethical implications of neuroimaging, neurogenetics, neuropharmacology, and neurotechnology. For teachers interested in incorporating neuroethics into their classrooms, the Center for Neuroscience & Society at the University of Pennsylvania (www.neuroethics.upenn.edu/resources/teaching-resources) maintains an extensive list of neuroethics educational resources. In addition to videos about neuroethics, the website has lesson plans for high school classrooms and a list of films and literature that feature neuroethical issues. The syllabi for undergraduate courses that are available from this website could also be adapted for younger students. Fictional case studies with accompanying questions that can prompt discussions about neuroethics can be downloaded from the Center for Sensorimotor Neural Engineering website (csne-erc.org/sites/default/files/CSNE%20Neuroethics%20Cases_for%20distribution.pdf). For teachers interested in a broader perspective on bioethics, Hawkins and Stark (2015) provide descriptions of online teaching resources. High school students interested in cognitive neuroscience and neuroethics can attend the Duke Neuro Camp, a summer program hosted by Duke University (www.learnmore.duke.edu/youth/neuro/index.asp). The neuroethics page on the Neuroscience for Kids website (https:// faculty.washington.edu/chudler/neuroe.html) offers readings and a series of discussion questions for younger students about challenging ethical issues involved in the fields of neuroscience and neural engineering.

CONCLUSION

Students who are exposed to the interdisciplinary field of neural engineering may discover new career pathways:

- Audiology and speech sciences
- Applied mathematics
- Biology
- Biomechanics
- Biomedical engineering/bioengineering
- Biophysics

- Cognitive sciences
- Computational neuroscience
- Computer science
- Electrical engineering
- Materials science
- Mechanical engineering
- Microsystems engineering
- Nanosystems engineering
- Neuroanatomy
- Neurobiology
- Neuroethics
- Neurology
- Neurosurgery
- Neuroscience
- Philosophy (neuroethics; disability studies)
- Physiology
- Psychology
- Rehabilitation medicine
- Robotics engineering
- Tissue engineering

The time is ripe to enter this field, as shown by recent investments in large-scale projects such as the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative and the Human Brain Project. Since the BRAIN Initiative was approved in 2013, five federal agencies have allocated hundreds of millions of dollars of funding to BRAIN-related neurotechnology research (White House, 2014), which has been supplemented by millions of dollars committed by the public and private sector to support these research efforts.

Science teachers are challenged to integrate contemporary science topics and engineering design into their curricula. At the secondary level, the topic of neural engineering aligns with disciplinary core ideas across physical and life sciences while demonstrating authentic connections to math, technology, and engineering. The combination of emerging technologies, cutting-edge science, and high-tech devices makes neural engineering an exciting topic for teachers and their students. For students who participate in robotics, coding, gaming, and maker communities, the integration of neural engineering into their science classrooms may strengthen connections between their home–school identities.

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