EDITORIAL
Using Open Neuroscience to Advance Equity in the Pedagogy and Research Infrastructure in Colleges/Universities Still Financially Impacted by COVID-19: The Emergence of a Global Resource Network Aimed at Integrating Neuroscience and Society

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Over the last two decades, technological developments have provided tools to facilitate the local manufacture of instruments and devices using an "open source" framework for online sharing of software and product designs. The same approach has been adopted by neuroscientists who have begun to develop a wide range of "open neuroscience"-based software and hardware (Raymond, 1999), open educational resources for neuroscience (Leussis, 2022), and more recently, open neuroscience datasets. The utility of open neuroscience tools accelerated greatly after the patent expiration of 3D-printers, which promulgated the integration of open-source software and hardware (Bechtold, 2016; Lee and Kim, 2015). This enabled researchers to print their own equipment components for use in both the laboratory and in STEM education (Baden et al., 2015; Canessa et al., 2013), such as an automated XYZT fluorescence imaging system (Wincott et al., 2021), a histology slide auto-stainer (Ponzetti et al., 2022), or optogenetics tools for zebrafish, *Drosophila*, and *C. elegans* (see Chagas et al., 2017).

Open source neuroscience tools can vary considerably by sub-discipline, but the following examples illustrate some impactful applications: Deep Learning Tools for measuring a wide range of animal behaviors (Mathis and Mathis, 2020), *Spikeling* for simulating spiking neurons *in-silica* (Baden et al., 2018), *Ephys* for a range of electrophysiological *in-vitro* data acquisition protocols (Suter et al., 2010), *PsychoPy* to generate a wide range of visual and auditory experimental stimuli (Peirce, 2009), *iCub* to employ robotics to investigate cognitive development (Tsagarakis et al., 2007), *Cognitive Neuroscience 2.0* to build a cumulative science on human brain function (Yarkoni et al., 2010), *FieldTrip* for advanced analyses of MEG, EEG, and invasive electrophysiological recordings (Oostenveld et al., 2011), as well as applications for studies of the connectome (Milham, 2012) and in cognitive neuroscience (Poldrack, 2012). These examples are important as they show the creativity in the breadth and depth by which open-source neuroscience tools have begun and continue to shape the pedagogical landscape in a more cost effective and equitable way than has previously been considered.

The global coronavirus-19 (COVID-19) pandemic caused even greater equity gaps, while also catalyzing further adoption of open neuroscience resources, as it forced neuroscientists to utilize open-source data, software, and hardware to continue their research while in lockdown (e.g., Gagné and Franzen, 2023) or contemplate leaving the neuroscience field (Vlisides et al., 2021). These same developments may now also offer new opportunities for applications in STEM education (Neuwirth et al., 2020). The expanding adoption of open neuroscience tools in STEM education has the potential to address existing inequities, as commercial off-the-shelf equipment is less affordable to public universities, particularly primarily undergraduate institutions (PUIs) and minority serving intuitions (MSIs). This chasm in access to cutting-edge instructional neuroscience resources between research-intensive institutions and those serving a broader student populace is detrimental because of four critical and often overlooked equity issues within the delivery of effective neuroscience pedagogy. First, it creates disproportionately larger academic achievement gaps (Neuwirth et al., 2020; Mukherji et al., 2017). Second, it fails to offer a more meaningful modern neuroscience curriculum (Colpitts et al., 2019; Yusuf et al., 2014). Third, it falls short of producing enhanced practical and computational skills that come from thoughtful and intentional research engagement necessary for the next generation of neuroscientists (Ramirez, 2020; Buffalari et al., 2020; Chase et al., 2020; Gage, 2019; Litt, 2015). Fourth, it fails to address the neuroscience problems occurring in society that require increased diversity in the workforce (Neuwirth et al., 2021; Bayline et al., 2020).

Here, we provide to educators an initial road-map on where to find high-impact open-source neuroscience software and hardware that can be quickly and easily accessed without specialized tools for neuroscience undergraduate education (Penner et al., 2021). This editorial emerged from a 4-day workshop on Open Neuroscience Software and Hardware, funded by The Dana Foundation (Canli, PI and Chagas, Instructor) and conducted at Stony Brook University with the following

Software Name	***Website***	***Mac/PC/Linux Compatible***	***Summary***
Napari	https://napari.org/	All	Image visualization/analysis suite
Open eye track	https://github.com/chand-lab/openEyeTrack	Linux	Fast eye tracker
Pirecorder	https://jollejolles.github.io/pirecorder/	Raspberry Pi	Camera recording system based on Raspberry Pi card sized computer
jsPsych	https://www.jspsych.org	Web browser based	
Bonsai-RX	https://bonsai-rx.org/	Windows	A suite to design and analyze experiments of all sorts. Several plugins and hardware Integration made easy.
Deeplabcut	http://www.mackenziemathislab.org/deeplabcut	All	Markless movement tracking using deep neural networks
TGAC browser	http://browser.tgac.ac.uk/	Web browser	Genomic browser to visualize annotations from Ensembl database Schema
OME	https://www.openmicroscopy.org/	All	OME is a consortium of universities, research labs, industry and developers producing open-source software and format standards for microscopy data.
MicroManager	http://www.micro-manager.org	All	Suite for microscope control. It allows control of systems that are no longer supported by manufacturers.
CellFinder	https://github.com/brainglobe/cellfinder	All	Automated 3D cell detection from whole-brain images
Neurodata without Borders	https://www.nwb.org/	All	Data Standard for neurophysiology.
JASP	https://jasp-stats.org/	All	Statistics software without programming (includes frequentist and Bayesian analysis)
Open Source Brain	https://www.opensourcebrain.org/	All	Computational models of neural systems
Computational Neuroscience	https://github.com/asoplata/open-computational-neuroscience-resources	All	Open Computational Neuroscience Resources
Open BCI	https://openbci.com/	All	Open-source tools for biosensing and neuroscience

Table 1. Open-source neuroscience software and related online communities.

Hardware Name	***Website***	***Mac/PC/Linux Compatible***	***Summary***
OpenFlexure	https://openflexure.org/	N/A	The OpenFlexure project makes high precision mechanical positioning available to anyone with a 3D printer - for use in microscopes, micromanipulators, and more.
UC2	https://github.com/openUC2/UC2-GIThisto	N/A	Microscopy modular toolkit, recipes include light sheet, holographic microscope and more.
HistoEnder	https://www.sciencedirect.com/science/article/pii/S2468067222001158	N/A	Automated histology with an adapted 3D printer.
Spikeling	https://journals.plos.org/plosbiology/article?id=10.1371/journal.pbio.2006760	Windows	In silico model of an artificial neuron.
PocketPCR	https://gaudi.ch/PocketPCR/	N/A	5 sample portable PCR machine.
Open Source Automated Western Blot	https://www.sciencedirect.com/science/article/pii/S2468067219300525	N/A	A 3D printed automated system for western blotting.
Small cost efficient 3D printed peristaltic pumps	https://www.sciencedirect.com/science/article/pii/S2468067220300249	N/A	A low-cost, easy to fabricate, SLA-3D-printed peristaltic pump for multi-channel systems in any lab.
BioAmp EXG pill	https://github.com/upsidedownlabs/BioAmp-EXG-Pill	All	A portable bioamplifier for ECG, EMG, EOG and EEG.
GOSH	https://openhardware.science/	N/A	A global community of open science hardware users, developers and researchers.
Open Source Hardware Association	https://www.oshwa.org/	N/A	US based association fostering knowledge development and fair use of open-source hardware.

Table 2. Open-source neuroscience hardware and related online communities.

participating institutions: The State University of New York (SUNY) Stony Brook; SUNY Old Westbury; Brooklyn College of The City University of New York (CUNY); and Lincoln University (PA).

(1) A Small Distillation of Open Neuroscience Software and Hardware Resource Links

The introductory phase of the workshop focused on the history and applications of 3D-printing in neuroscience These lectures and demonstrations compiled a rich set of resources to teach faculty how to 3D-print and build their own equipment for their pedagogy and research. Tables 1 and 2 offer some examples of open neuroscience tools for a wider audience to consider using as alternatives to their pedagogy and research interests (for a wider range of projects and tools, visit https://open-neuroscience.com).

(2) "Open-Source Neuroscience" Meets "Neuroscience and Society": A Timely Pedagogy Resource for Underfunded Programs

The workshop was inspired by a non-governmental organization (NGO) named *Teaching and Research in Natural Sciences for Development for Africa*; TReND in Africa, https://trendinafrica.org) which pioneered a curriculum for self-empowered capacity-building in neuroscience in Africa, in collaboration with the "Open Neuroscience" online platform (https://open-neuroscience.com). Constraints in funding and access are not, however, limited to the Global South. Even in prosperous nations as the United States, significant imbalances exist among neuroscience researchers and educators across institutions – creating the impetus to bring NGO-African-born resourcefulness to the United States. Whereas the original course is based on an intensive two-week format that introduces neuroscientists into the "how-to's" of 3D-printing, electronics, and software design, its U.S. version was modified to accommodate the realities of the time demands that are placed on faculty from PUIs/MSIs. The "DNA" of the program, however, remained true to its origin: to build capacity in neuroscience research and education by training faculty in the basic open neuroscience tools, and empowering them to continue expanding these capacity-building tools through ongoing community support well past the course's formal conclusion.

Capacity-building using open neuroscience principles extends beyond STEM education, by encouraging both instructors and their students to envision applications to solve societal problems. For example, electroencephalography (EEG) studies commonly exclude individuals of African descent, whose coarse hair is not well-suited for standard EEG devices that require access to the scalp (Louis et al., 2022). This systematic exclusion of select groups of people creates a knowledge gap that stands as an obstacle to addressing significant societal challenges, such as the high incidence rates of epilepsy in African nations, which may be twice that of Asia, Europe, and North America (Ba-Diop et al., 2014). To address this problem, new kinds of EEG electrodes were developed recently, using open neuroscience tools (Etienne et al., 2020) to make EEG research more inclusive through intentional efforts to become diverse and more equitable in order to best inform future scientific efforts within- and between distinct populations.

(3) Open-Source Neuroscience Can Creatively Address the 3Rs in Animal Research

Current students are more sensitive than past generations to the use of animals and have a desire to reduce the number of animals used for research purposes. The alternatives to animal-based dissections associated neuroanatomy, and neurophysiology demonstrations, can also be successful for training students while being cost-effective and learner inclusive (Neuwirth et al., 2018). Russel and Burch (1959) proposed the 3-Rs that aim to identify and use animal Replacement, Reduction, and Refinement with alternatives whenever possible to prevent the unnecessary use of animals in biomedical research. From the 4-day workshop, the team from SUNY Old Westbury intentionally sought to 3D-print rat skulls to be used as a procedural training tool for teaching students and researchers on how to perform craniotomies for a wide-range of neurosurgical applications. This use of 3D-printing replaces the use of animals, and can serve to upskill and reskill students or researchers to become more proficient in advanced and dynamic skills. Hands-

Team	***Problem in Neuroscience***	***3D Printed equipment***
Old Westbury	No rat brain sized cryomolds	Cryomolds tall enough to fit full rat brain for either coronal or sagittal sectioning
	No training skull models for teaching rodent surgical craniotomies	Adult rat skulls to reduce use of animals in training craniotomies
	Expensive interactive models for cell organelles, spinal cord projections, and deep brain regions	3D printed neuronal cell structure and processes, neuronal projections in the CNS/PNS, and deep brain regions
	Automated stereotaxic surgery are very expensive	Reconfigure and reprogram a 3D printer to perform stereotaxic drilling for brain access
Brooklyn College	Specialized cameras for microscopes are expensive	3D printed smartphone holder
	Replacements for Lost/damaged electrode holders take time to receive	3D printed replacements
	Implanted micromanipulator/ electrode holder for various small animal models limited or unavailable	3D printed head stage micromanipulators are light and customizable for unique species and applications (Rogers et al. 2017)
Lincoln University	Limited behavioral tests and tools for *C. elegans*	T-maze scaled down for *C. elegans*

Table 3. 3D printed equipment developed to solve a neuroscience educational and/or research problem.

on applied learning opportunities to implement "dry-runs" of any technical skill provide a clear and ethical means to teach next generation neuroscientists while reducing the use of animals and closing equity gaps.

(4) Thinking Forward and Promoting a Culture Shift Towards Open Neuroscience Resources

From the 4-day workshop on open neuroscience software, hardware, and 3D-printing, the teams of neuroscientists were able to come up with several solutions to different problems in the field by 3D-printing neuroscience equipment, which could be used effectively for research and teaching, and to foster student engagement (Table 3). The teams also learned about the value of integrating open neuroscience principles into the curriculum and discussed including 3D-printing as a module in methods courses to empower students to create new tools to solve problems.

IN SUMMARY

The field is approaching an inflection point in transforming neuroscience STEM education by means of open neuroscience. Workshops can serve to promote awareness and garner more interest for open-source neuroscience accessibility, low-cost alternatives, and creative solutions to scientific questions and to societal problems. As more global networks share their experiences, data, software, hardware, and integrated solutions, much can be learned from universities/colleges in developing countries that can serve underfunded universities/colleges in the United States, creating greater equity for students across institutions. What is clear is that the future of neuroscience does not need to rely heavily upon costly equipment to do important and impactful science. With open neuroscience, universities/colleges may not have to become reliant on grant money to acquire such equipment to be competitive and have the opportunity to publish in top-quality neuroscience journals. When expensive equipment was not a barrier, resourcefulness and creativity were all one needed to investigate a scientific problem and to disseminate one's findings publicly. Today, technology pressures have made a majority of current and next-generation neuroscientists reliant on such equipment, constraining their creativity. Additionally, 3D-printing and technological advancements offer a modern vehicle for high-throughput of creativity and the arts, making such ingenuity swift-paced and efficient to circumvent the aforementioned challenges. Perhaps, one can consider in some ways that STEAM is the best suited linkage with open-source neuroscience. Given the continued challenges posed by COVID-19 and the associated financial hardships, new solutions and creative alternatives are more important than ever before. However, as new efforts continue to shape, mold, and hopefully solidify the use of open-source neuroscience software and hardware integrated technologies, we may experience a culture shift towards more creative scientific sharing, collaboration and innovation that globally serves neuroscience and society.

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