Preview of Award 1827565 - Final Project Report

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Cover

Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Grant or Other Identifying Number Assigned by Agency:	1827565
Project Title:	PFI-TT: Software for Automated Real-time Electroencephalogram Seizure Detection in Intensive Care Units
PD/PI Name:	Iyad Obeid, Principal Investigator Joseph Picone, Co-Principal Investigator
Recipient Organization:	Temple University
Project/Grant Period:	08/01/2018 - 09/30/2021
Reporting Period:	08/01/2021 - 09/30/2021
Submitting Official (if other than PD\PI):	Joseph Picone Co-Principal Investigator
Submission Date:	03/08/2022
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	Joseph Picone

Accomplishments

*** What are the major goals of the project?**

There were three main goals of this project: **(1) technology enhancement:** close the gap on performance between our state of the art system and clinically acceptable performance,**(2) technology hardening:** create a real-time system that is capable of being deployed into clinical environments and support clinical testing, and **(3) technology evaluation:** evaluate the system on a previously unseen data set to demonstrate that performance translates to a broad range of clinical operating conditions. The expected impact of these three goals is that the research system developed previously under SBIR funding should be transformed into a commercially viable product.

*** What was accomplished under these goals and objectives (you must provide information for at least one of the 4 categories below)?**

Major Activities:

We spent the majority of time on this project pursuing goals no. 1 and no. 2 above. Goal no. 1 was particularly critical an overarching goal of the project was to reduce the gap between performance expectations of customers and our best technology. We allocated a PhD student to this task and his work formed the basis of his dissertation.

Goal no. 2 was very important from a commercialization standpoint. Most published research systems are not suitable for clinical applications because they perform multiple passes over the data and have extreme amounts of latency. Performance tends to suffer as latency is reduced. A major differentiation of our work is that we have produced a high performance system that operates with minimal latency and requires modest computing resources to operate in real-time.

The final goal, technology evaluation leading to commercialization, was difficult to achieve due to a variety of reasons. We did conduct the industry's first widescale technology evaluation to calibrate the performance of the best research systems. That effort is described below. However, our efforts to commercialize the technology through are start up stalled because we were not able to continue funding for our start up company (our Phase II SBIR was not funded). Our efforts to market the technology to leading technology vendors in the field were also not successful. Therefore, at the conclusion of the project, we have made the technology open source so that others can build on our work.

Specific Objectives:

With respect to goal no. 1, we have for a long time established three performance goals for the system: (1) 75% sensitivity, (2) less than 1 false alarm (FA) per 24 hours, and (3) less than 2 seconds of latency. This level of performance was established as a result of discussions with over 100 potential customers over the past 5 years (as part of an NSF I-CORPS project).

Sensitivity degrades very quickly as the FA rate approaches 1/24. hr. This is an extreme operating point not addressed by most machine learning research. Many algorithms are incapable of operating at such a low FA rate. For example, deep learning systems are notorious for the high-level of confidence produced even for incorrect hypotheses (we often joke that they are very sure of themselves). It is difficult to dial down their performance to this very low FA range.

Low latency is critical for clinical deployment of this technology. Neurologists want to be able to medicate patients and see the results instantly. High performing systems that involve multiple passes over the data, such as those entered in the Neureka Challenge described below, are simply not useful in clinical settings because they operate on an entire signal after collection has been completed. The techniques used by these systems to reduce false alarms and remove artifacts are simply not transferable to real-time systems. Therefore, a major objective of our research was to reduce the latency of our best performing system to less than 2 seconds, while operating in real-time on a 1.7 GHz processor.

Finally, with respect to our third goal, we took advantage of a unique opportunity to conduct an industry-wide technology evaluation through the Neureka 2020 Epilepsy Challenge. This was a great opportunity to establish industry-accepted benchmarks for the technology, and to accelerate progress in the field. This challenge is described in detail in:

Shah, V., Obeid, I., Picone, J., Ekladious, G., Iskander, R., & Roy, Y. (2020). Validation of Temporal Scoring Metrics for Automatic Seizure Detection. In I. Obeid, I. Selesnick, & J. Picone (Eds.), *Proceedings of the IEEE Signal Processing in Medicine and Biology Symposium (SPMB)* (pp. 1–5). https://doi.org/10.1109/SPMB50085.2020.9353631.

The web site for the challenge is here: https://neureka-challenge.com/.

We also improved the robustness of the system to variations in recording conditions. Deep learning systems are well-known for lacking robustness to unseen data. We investigated this and demonstrated that our performance results transfer across databases, vendor equipment and recording conditions.

Significant Results:

With respect to the first activity, our best research system, which we refer to as the baseline system for this grant, is fully described in Vinit Shah's PhD dissertation (Shah, 2021), which was successfully defended in May 2021. This dissertation represents the cumulative work of one of our two students who initiated our work in automatic seizure detection. The central thesis of his work is that separation of the seizure detection problem into a two-phase problem – epileptiform activity detection followed by seizure detection – should improve our ability to detect and localize seizure events. In the first phase, we used a sequential neural network algorithm known as a long short-term memory (LSTM) network to identify channel-specific epileptiform discharges associated with seizures. In the second phase, the feature vector is augmented with posteriors that represent the onset and offset of ictal activities. These augmented features are applied to a multichannel convolutional neural network (CNN) followed by an LSTM network.

The multiphase model was evaluated on a blind evaluation set and was shown to detect segment boundaries within a -second margin of error. Our previous best system, which delivers state-of-the-art performance on this task, correctly detected only 9 segment boundaries. Our multiphase system was also shown to be robust by performing well on two blind evaluation sets. Seizure detection performance on the TU Seizure Detection (TUSZ) Corpus development set is sensitivity with false alarms/ hours (FAs/24 hrs). Performance on the corresponding evaluation set is sensitivity with FAs/ hrs. Performance on a previously unseen corpus, the Duke University Seizure (DUSZ) Corpus is sensitivity with FAs/ hrs. Our previous best system yields sensitivity with FAs/ hrs on the TUSZ development set, sensitivity with 1 FAs/ hrs on the TUSZ evaluation set and sensitivity with FAs/ hrs on DUSZ.

Our second student, Meysam Golmohammadi, who pioneered our work on applying deep learning to seizure detection and was the Chief Technical Officer of our start up, Biosignal Analytics Inc., also successfully defended his dissertation (Golmohammadi, 2021) in June 2021. This dissertation represents a summary of our initial work understanding the problem and addressing it by leveraging our years of experience with other applications such as speech recognition. Automatic analysis of clinical EEGs is a very difficult machine learning problem due to the low fidelity of a scalp EEG signal. Deep learning approaches can be viewed as a broad family of neural network algorithms that use many layers of nonlinear processing units to learn a mapping between inputs and outputs. Deep learning-based systems have generated significant improvements in performance for sequence recognitions tasks for temporal signals such as speech and for image analysis applications that can exploit spatial correlations, and for which large amounts of training data exists. The primary goal of this research was to develop deep learning-based architectures that capture spatial and temporal correlations in an EEG signal. We applied these architectures to the problem of automated seizure detection for adult EEGs. The main contribution of this work is the development of a high-performance automated EEG analysis system based on principles of machine learning and big data that approaches levels of performance required for clinical acceptance of the technology.

With respect to the second goal of developing a real-time system, the process of engineering the system to be amenable to a real-time implementation is discussed in Khalkhali et al. (2021). Scalp electroencephalogram (EEG) signals inherently have a low signal-to-noise ratio due to the way the signal is electrically transduced. Temporal and spatial information must be exploited to achieve accurate detection of seizure events. Most popular approaches to seizure detection using deep learning focus on modeling temporal or spatial information, but do not jointly model this information. We exploit both simultaneously by converting the multichannel signal to a grayscale image and using transfer learning approaches to achieve high performance. The proposed system is trained end-to-end with only very simple pre- and post-processing operations which are computationally lightweight and have low latency, making them

conducive to clinical applications that require real-time processing. We demonstrate the efficacy of this approach We have achieved a performance of 42.05% sensitivity with 5.78 false alarm per 24 hours on the development dataset of v1.5.2 of the Temple University Hospital Seizure Detection Corpus. The system can run easily run in real-time using single core CPU, operating at 0.58 xRT on a 1.7 GHz processor in 16 Gbytes of memory with a latency of 300 msec.

With respect to the third major activity, in Golmohammadi's study, we used the Temple University EEG (TUEG) Corpus, supplemented with data from Duke University and Emory University, to evaluate the performance of these hybrid deep structures. We demonstrated that performance of a system trained only on Temple University Seizure Corpus (TUSZ) data transfers to a blind evaluation set consisting of the Duke University Seizure Corpus (DUSZ) and the Emory University Seizure Corpus (EUSZ). This type of generalization is very important since complex high-dimensional deep learning systems tend to overtrain.

We also investigated the robustness of this system to mismatched conditions (e.g., train on TUSZ, evaluate on EUSZ). We train a model on one of three available datasets and evaluate the trained model on the other two datasets. These datasets are recorded from different hospitals, using a variety of devices and electrodes, under different circumstances and annotated by different neurologists and experts. Therefore, these experiments help us to evaluate the impact of the dataset on our training process and validate our manual annotation process.

Further, we introduce methods to improve generalization and robustness. We analyze performance to gain additional insight into what aspects of the signal are being modeled adequately and where the models fail. The best results for automatic seizure detection achieved in this study are with FA per hours on TUSZ, with FAs on DUSZ, and with 11.26 FAs on EUSZ. We demonstrate that the performance of the deep recurrent convolutional structure presented in this study is statistically comparable to the human performance on the same dataset.

Finally, in Golmohammadi's work, we also developed some effective visualization tools to understand exactly what the network is learning. We believe these tools will be relevant to a larger class of deep learning systems.

References

Golmohammadi, M. (2021). *Deep Architectures for Spatio-Temporal Sequence Recognition With Applications in Automatic Seizure Detection* [Temple University]. *https://doi.org/https://www.isip.piconepress.com/publications/phd_dissertations/2021/seizure_detection/*

Khalkhali, V., Shawki, N., Shah, V., Golmohammadi, M., Obeid, I., & Picone, J. (2021). Low Latency Real-Time Seizure Detection Using Transfer Deep Learning. In I. Obeid, I. Selesnick, & J. Picone (Eds.), *Proceedings of the IEEE Signal Processing in Medicine and Biology Symposium (SPMB)* (pp. 1–7). IEEE. *https://doi.org/10.1109/SPMB52430.2021.9672285.*

Shah, V. (2021). *Improved Segmentation for Automated Seizure Detection Using Channel-Dependent Posteriors* [Temple University]. *https://www.isip.piconepress.com/publications/phd_dissertations/2021/seizure_segmentation/*

Key outcomes or Other achievements:

In Spring 2020, we had a unique opportunity to coordinate an industry-wide challenge on seizure detection. We collaborated with several partners and designed the Neureka 2020 Epilepsy Challenge. Initially, 19 sites participated. We provided the data sets and evaluation methodology. The results, as mentioned before, are available from this web site: *https://neureka-challenge.com/*. It established an industry accepted benchmark for the performance of the technology. However, the best performing systems were not easily translated to real-time technology and involved complex, multi-pass systems. The previously mentioned real-time system we have developed compares favorably with the best systems but is much more amenable to real-time implementation (which we provide). The Neureka Challenge was a unique opportunity to baseline our technology, presumably making it more attractive for commercialization.

We have continued to support participants in this evaluation. We routinely run evaluations for researchers on the blind evaluation data set to support their publications as a community service. We are also going to release the blind evaluation data as part of TUSZ v1.5.3 (expected in Spring 2022).

*** What opportunities for training and professional development has the project provided?**

Students involved in this project often enter the project will little or no software experience. We provide extensive training on Linux-based computing, software development in C++ and Python, and a variety of project management tools. We also encourage our students to publish at our annual conference. The skills they develop allow them to transition into summer internships in industry, where they gain even more valuable skills relevant to their careers. We spend a lot of time assisting these students in their job searches.

*** Have the results been disseminated to communities of interest? If so, please provide details.**

In addition to distributing information through our very active listserv, we maintain a project web site and disseminate data,resources, and software through our well-known EEG web site: *https://www.isip.piconepress.com/projects/tuh_eeg/*. The project specific web site is here: *https://isip.piconepress.com/projects/nsf_pfi_tt/*.

We also host an annual conference at which we publish our EEG-related research. Both our graduate students and undergraduates participate in this conference by presenting papers and posters on our EEG research. The archives of the conference are indexed in IEEEXplore. The conference web site is located here: *https://www.ieeespmb.org/*.

Supporting Files

Filename	Description	Uploaded By	Uploaded On

Filename	Description	Uploaded By	Uploaded On
roc.pdf	Receiver Operating Characteristics (ROC) comparing the three significant EEG seizure detection systems we have developed.	Joseph Picone	03/08/2022
table.pdf	A comparison of our EEG seizure detection system to several competitive systems that participated in our open source challenge. Our system is the only one of these that can be implemented in real-time and used in clinical applications.	Joseph Picone	03/08/2022

Products

Books

Book Chapters

Khalkhali, V., Shawki, N., Shah, V., Golmohammadi, M., Obeid, I., & Picone, J. (2023). Low Latency Real-Time Seizure Detection Using Transfer Deep Learning. *Signal Processing in Medicine and Biology: Innovation and Applications (Tentative) 1st.* 1. Obeid, Iyad Selesnick, Ivan Picone, Joseph. Spring Verlag. New York, New York, USA. . Status = OTHER; Acknowledgement of Federal Support = Yes ; Peer Reviewed = Yes ; OTHER: N/A.

Inventions

Journals or Juried Conference Papers

View all journal publications currently available in the NSF Public Access Repository for this award.

The results in the NSF Public Access Repository will include a comprehensive listing of all journal publications recorded to date that are associated with this award.

Shawki, N. and Elseify, T. and Cap, T. and Shah, V. and Obeid, I. and Picone, J.. (2020). A Deep Learning-Based Real-time Seizure Detection System. *Proceedings of the IEEE Signal Processing in Medicine and Biology Symposium (SPMB)*. 1 (1) . Status = Deposited in NSF-PAR doi:https://doi.org/10.1109/SPMB50085.2020.9353623 ; Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 10/29/2020) Full text Citation details

Khalkhali, Vahid Shawki. (2021). Low Latency Real-Time Seizure Detection Using Transfer Deep Learning. *Proceedings of the IEEE Signal Processing in Medicine and Biology Symposium (SPMB)*. . Status = Deposited in NSF-PAR Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 12/29/2021) Full text Citation details

Buckwalter, Grace Chhin. (2021). Recent Advances in the TUH EEG Corpus: Improving the Interrater Agreement for Artifacts and Epileptiform Events. *Proceedings of the IEEE Signal Processing in Medicine and Biology Symposium (SPMB)*. . Status = Deposited in NSF-PAR Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 12/29/2021) Full text Citation details

Roy, Subhrajit and Kiral, Isabell and Mirmomeni, Mahtab and Mummert, Todd and Braz, Alan and Tsay, Jason and Tang, Jianbin and Asif, Umar and Schaffter, Thomas and Ahsen, Mehmet Eren and Iwamori, Toshiya and Yanagisawa, Hiroki and Poonawala, Hasan and Madan, Piyush and Qin, Yong and Picone, Joseph and Obeid, Iyad and Marques, Bruno De and Maetschke, Stefan and Khalaf, Rania and Rosen-Zvi, Michal and Stolovitzky, Gustavo and Harrer, Stefan. (2021). Evaluation of artificial intelligence systems for assisting neurologists with fast and accurate annotations of scalp electroencephalography data. *EBioMedicine*. 66 (C) 103275. Status = Deposited in NSF-PAR doi:https://doi.org/10.1016/j.ebiom.2021.103275 ; Federal Government's License = Acknowledged. (Completed by Picone, null on 09/30/2021) Full text Citation details

Ferrell, Sean and Mathew, Vineetha and Refford, Matthew and Tchiong, Vincent and Ahsan, Tameem and Obeid, Iyad and Picone, Joseph. (2020). The Temple University Hospital EEG Corpus: Electrode Location and Channel Labels. *Institute for Signal and Information Processing Report*. 1 (1) 1-9. Status = Deposited in NSF-PAR doi:https://doi.org/ ; Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 10/29/2020) Full text Citation details

Shah, Vinit and Golmohammadi, Meysam and Obeid, Iyad and Picone, Joseph. (2021). Objective Evaluation Metrics for Automatic Classification of EEG Events. *Biomedical Signal Processing: Innovation and Applications*. 1 (1) 1-26. Status = Deposited in NSF-PAR doi:https://doi.org/ ; Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 10/29/2020) Full text Citation details

Jean-Paul, S. and Elseify, T. and Obeid, I. and Picone, J.. (2019). Issues in the Reproducibility of Deep Learning Results. *IEEE Signal Processing in Medicine and Biology Symposium (SPMB)*. 1 (1) 1 to 4. Status = Deposited in NSF-PAR doi:https://doi.org/10.1109/SPMB47826.2019.9037840 ; Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 10/29/2020) Full text Citation details

Ochal, Domenic and Rahman, Safwanur and Ferrell, Sean and Elseify, Tarek and Obeid, Iyad and Picone, Joseph. (2020). The Temple University Hospital EEG Corpus: Annotation Guidelines. *Institute for Signal and Information Processing Report*. 1 (1) 1-28. Status = Deposited in NSF-PAR doi:https://doi.org/ ; Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 10/29/2020) Full text Citation details

Rahman, Safwanur Hamid. (2020). Improving the Quality of the TUSZ Corpus. *IEEE Signal Processing in Medicine and Biology Symposium (SPMB)*. 1 (1) 1-5. Status = Deposited in NSF-PAR doi:https://doi.org/ ; Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 10/29/2020) Full text Citation details

Shah, Vinit and Obeid, Iyad and Picone, Joseph and Ekladious, George and Iskander, Ray and Roy, Yannick. (2020). Validation of Temporal Scoring Metrics for Automatic Seizure Detection. *Proceedings of the IEEE Signal Processing in Medicine and Biology Symposium (SPMB)*. 1 (1) 1-5. Status = Deposited in NSF-PAR doi:https://doi.org/ ; Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 10/29/2020) Full text Citation details

Hamid, Ahmed and Gagliano, Katherine and Rahman, Safwanur and Tulin, Nikita and Tchiong, Vincent and Obeid, Iyad and Picone, Joseph. (2020). The Temple University Artifact Corpus: An Annotated Corpus of EEG Artifacts. *IEEE Signal Processing in Medicine and Biology Symposium SPMB*. 1 (1) 1. Status = Deposited in NSF-PAR doi:https://doi.org/ ; Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 10/29/2020) Full text Citation details

Rahman, S. and Miranda, M. and Obeid, I. and Picone, J.. (2019). Software and Data Resources to Advance Machine Learning Research in Electroencephalography. *IEEE Signal Processing in Medicine and Biology Symposium (SPMB)*. 1 (1) 1 to 4. Status = Deposited in NSF-PAR

doi:https://doi.org/10.1109/SPMB47826.2019.9037851 ; Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 10/29/2020) Full text Citation details

Golmohammadi, Meysam and Shah, Vinit and Obeid, Iyad and Picone, Joseph. (2020). Deep Learning Approaches for Automatic Seizure Detection from Scalp Electroencephalograms. *Signal Processing in Medicine and Biology: Emerging Trends in Research and Applications*. 1 (1) 233-274. Status = Deposited in NSF-PAR doi:https://doi.org/10.1007/978-3-030-36844-9 ; Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 10/29/2020) Full text Citation details

Kiral, Isabell and Roy, Subhrajit and Mummert, Todd and Braz, Alan and Tsay, Jason and Tang, Jianbin and Asif, Umar and Schaffter, Thomas and Mehmet, Eren and Picone, Joseph and Obeid, Iyad and Marques, Bruno De and Maetschke, Stefan and Khalaf, Rania and Rosen-Zvi, Michal and Stolovitzky, Gustavo and Mirmomeni, Mahtab and Harrer, Stefan and Yanagisawa, Hirki and Iwamori, Toshiya and Madan, Piyush and Qin, Yong and Ma, Li and Ti, Wei Lian and Liu, Wen and Mei, Jing and Hensley, Sharon and Chandra, Rachita and Hake, Paul and Henessy, Richard and Babaali, Parisa and Yuenreed, Gigi and Kather, Ryan and Arcos-Diaz, Dario and Cherner, Michael. (2019). The Deep Learning Epilepsy Detection Challenge: Design, Implementation, and Test of a New Crowd-Sourced AI Challenge Ecosystem. *Challenges in Machine Learning Competitions for All (CiML)*. 1 (1) 1-3. Status = Deposited in NSF-PAR doi:https://doi.org/ ; Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 10/29/2020) Full text Citation details

Lin, Rebecca and Marquez, Destiny and Jacobson, Mercedes and Castaldi, Hannah and Buckman, Samuel and Shah, Vinit and Picone, Joseph. (2020). Accuracy of Automated Machine Learning Software in Identifying EEGs with Prolonged Seizures. *Annual Meeting of the American Academy of Neurology (AAN)*. 1 (1) 1. Status = Deposited in NSF-PAR doi:https://doi.org/ ; Federal Government's License = Acknowledged. (Completed by Picone, Joseph on 10/29/2020) Full text Citation details

Khalkhali, V., Shawki, N., Shah, V., Golmohammadi, M., Obeid, I., & Picone, J. (2021). Low Latency Real-Time Seizure Detection Using Transfer Deep Learning. In I. Obeid, I. Selesnick, & J. Picone (Eds.), Proceedings of the IEEE Signal Processing in Medicine and Biology Symposium (SPMB) (pp. 1–7). Philadelphia, Pennsylvania, USA.. Status = PUBLISHED.

Buckwalter, G., Chhin, S., Rahman, S., Obeid, I., & Picone, J. (2021). Recent Advances in the TUH EEG Corpus: Improving the Interrater Agreement for Artifacts and Epileptiform Events. In I. Obeid, I. Selesnick, & J. Picone (Eds.), Proceedings of the IEEE Signal Processing in Medicine and Biology Symposium (SPMB) (pp. 1–3). Philadelphia, Pennsylvania, USA.. Status = PUBLISHED.

Licenses

Other Conference Presentations / Papers

Other Products
Audio or Video Products.

A video made for the NSF STEM DIVE competition that promotes our project.

URL: https://isip.piconepress.com/projects/nsf_pfi_tt/resources/videos/stem_dive/

Audio or Video Products.

A video that demonstrates real-time seizure detection.

URL: https://isip.piconepress.com/projects/nsf_pfi_tt/resources/videos/realtime_eeg_analysis/

Other Publications

Patent Applications

Technologies or Techniques

URL: https://isip.piconepress.com/projects/nsf_pfi_tt/resources/software/nedc_eeg_multiphase/

A software release of our multiphase EEG seizure detection system.

URL: https://isip.piconepress.com/projects/nsf_pfi_tt/resources/software/nedc_eeg_resnet/

A software release of our real-time EEG system.

Thesis/Dissertations
Golmohammadi, Meysam. *Deep Architectures for Spatio-Temporal Sequence Recognition With Applications in Automatic Seizure Detection*. (2021). Temple University. Acknowledgement of Federal Support = Yes

Shah, Vinit. *Improved Segmentation for Automated Seizure Detection Using Channel-Dependent Posteriors*. (2021). Temple University. Acknowledgement of Federal Support = Yes

Websites or Other Internet Sites
NSF PFI-TT: Real-time Analysis of Electroencephalograms in an Intensive Care Environment
https://isip.piconepress.com/projects/nsf_pfi_tt/

This web site encapsulates all software, data and resources related to the project.

Supporting Files

Filename	Description	Uploaded By	Uploaded On
website.pdf	A screenshot of the project web site used as a permanent archive of the project.	Joseph Picone	02/21/2022

Participants/Organizations

Research Experience for Undergraduates (REU) funding

Form of REU funding support:	REU supplement
How many REU applications were received during this reporting period?	12
How many REU applicants were selected and agreed to participate during this reporting period?	4
REU Comments:	

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Obeid, Iyad	PD/PI	1
Picone, Joseph	Co PD/PI	1
Shah, Vinit	Graduate Student (research assistant)	12
Shawki, Nabila	Graduate Student (research assistant)	3
Alexander, Carmel	Undergraduate Student	1
Buckwalter, Grace	Undergraduate Student	1
Cap, Thao	Undergraduate Student	3
Chhin, Sidney	Undergraduate Student	1
Elseify, Tarek	Undergraduate Student	3
Liang, Shu (Dennis)	Undergraduate Student	3
Miranda, Matthew	Undergraduate Student	2
Nguyen, Sarah	Undergraduate Student	1
Rahman, Safwanur	Undergraduate Student	6
Tchiong, Vincent	Undergraduate Student	6
Temory, Mir Muzamil	Undergraduate Student	1
Tulin, Nikita	Undergraduate Student	3
Vorwick, Lynn	Undergraduate Student	3

Full details of individuals who have worked on the project:

Iyad Obeid
Email: iobeid@temple.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: Bioengineering subject matter expert

Funding Support: None.

Change in active other support: No

International Collaboration: No
International Travel: No

Joseph Picone
Email: joseph.picone@gmail.com
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: Project management, technology development

Funding Support: None

Change in active other support: No

International Collaboration: No
International Travel: No

Vinit Shah
Email: tug14467@temple.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: Lead algorithm designer. Artifact reduction. Deep learning architectures.

Funding Support: None

International Collaboration: No
International Travel: No

Nabila Shawki
Email: tuk02200@temple.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Real-time implementation. Feature extraction development using augmented information.

Funding Support: Worked 9 months as a department teaching assistant prior to Summer 2019.

International Collaboration: No
International Travel: No

Carmel Alexander
Email: carmel.alexander@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Data Annotator

Funding Support: None

International Collaboration: No
International Travel: No

Grace Buckwalter
Email: grace.buckwalter@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Data Annotator

Funding Support: None

International Collaboration: No
International Travel: No

Thao Cap
Email: tuj64267@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 3

Contribution to the Project: Software engineer. Supports the development of some of software and infrastructure.

Funding Support: None

International Collaboration: No
International Travel: No

Sidney Chhin
Email: sidney.chhin@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Data Annotator

Funding Support: None

International Collaboration: No
International Travel: No

Tarek Elseify
Email: tug35668@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 3

Contribution to the Project: Web developer and software engineer. Tarek helped develop the user interface for the real-time demo and addressed issues with Python efficiency.

Funding Support: None

International Collaboration: No
International Travel: No

Shu (Dennis) Liang
Email: tul14986@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 3

Contribution to the Project: Web developer and content creator.

Funding Support: None

International Collaboration: No
International Travel: No

Matthew Miranda
Email: tuj66769@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 2

Contribution to the Project: Software engineer responsible for the development of the real-time system.

Funding Support: None

International Collaboration: No
International Travel: No

Sarah Nguyen
Email: sarah.nguyen0005@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Data Annotator

Funding Support: None

International Collaboration: No
International Travel: No

Safwanur Rahman
Email: tuh01696@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 6

Contribution to the Project: Data Annotator and Release Coordinator

Funding Support: None

International Collaboration: No
International Travel: No

Vincent Tchiong
Email: tug94380@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 6

Contribution to the Project: Data Annotator

Funding Support: None

International Collaboration: No
International Travel: No

Mir Muzamil Temory
Email: mirmuzamil_temory@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Data Annotator

Funding Support: None

International Collaboration: No
International Travel: No

Nikita Tulin
Email: tug47034@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 3

Contribution to the Project: Data Annotator and Release Manager

Funding Support: None

International Collaboration: No
International Travel: No

Lynn Vorwick
Email: tug70217@temple.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 3

Contribution to the Project: Software engineer responsible for design and testing of our Python code. Manages the released software and makes sure it conforms to our standards.

Funding Support: None

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?
Nothing to report.

Were other collaborators or contacts involved? If so, please provide details.

It is useful to report that the Department of Neurology at Temple University Hospital has been a continuous partner in this project from the very beginning at no cost to the project.

Impacts

What is the impact on the development of the principal discipline(s) of the project?

Through the development and release of open source seizure detection technology, we have created a number of unique resources that establish performance for state of the art technology. These efforts to normalize research in the field were supported by the Neureka 2020 Epilepsy Challenge previously described.

We maintain a listserv, which users sign up for, that now has over 5,500 members. We average one support request per day, typically from users needing help with understanding the data or searching for resources relevant to their project.The databases we provide are now used extensively throughout the EEG community to support their research. Customers are very appreciative of the resources we provide.The software we provide also helps these users learn how to process the data and how to implement their research efficiently.

We are doing a very effective job of increasing participation in the field by helping small research groups and individual researchers jumpstart their careers.

The low latency system we have developed is at a point where it is clinically useful. We continue to look for opportunites to commercial it and extend its capabiliites.

What is the impact on other disciplines?

We continue to promote the problem of achieving a low false alarm rate in machine learning throughout the community. Our results remind the community that there is a long way to go in developing effective deep learning systems for problems involving signal interpretation. Our software and tools, available at *https://isip.piconepress.com/projects/tuh_eeg/html/downloads.shtml*, continue to support, educate and inspire researchers.

We host an annual conference, the IEEE Signal Processing in Medicine and Biology Symposium, which will be in its 12th year in 2022. We now regularly see papers submitted that report results on our data. We also regularly answer support requests from researchers outside our immediate discipline looking to use our data for their research.

What is the impact on the development of human resources?

It is difficult to underestimate the impact the opportunity to work on this project has on our undergraduates. Many of these students would not get an opportunity to work on this type of research if it wasn't for our group. Once exposed to this research, students often get summer internships and full-time employment based on the skills they develop in this group. Also, since we often employ students from departments outside engineering, such as neuroscience, we often help these students find new career directions. Many of these students enter Temple thinking they want to go into traditional disciplines like medicine, but after their experiences in our group, they become much more interested in data science and software.

What was the impact on teaching and educational experiences?

The data and resources we develop are used in a wide range of classes including: Engineering Computation I (ECE 1111), Engineering Computation IV (ECE 4822), Senior Design (ENGR 4196/4296) and Introduction to Machine Learning and Pattern Recognition (ECE 8527). Students often use our data to test data-intensive programs, or conduct machine learning experimentson data sets we prepare for educational purposes.

Several educational institutions are using our data resources and visualization tools to support coursework in neuroscience and neurology. We routinely support these users with tutorials, software and documentation.

What is the impact on physical resources that form infrastructure?

We have developed a state of the art small computing cluster to host our data and resources. This cluster is used for our research, but also, to support upper-level and graduate-level education. We have published information about configurations andoften support other research groups in their attempts to replicate our computing environment.

This cluster, described here - *https://isip.piconepress.com/projects/neuronix/* - is unique in that we can move data between three computer networks in a secure fashion: Temple's main campus network, Temple's HIPAA-secured research network, and Temple University's main hospital network. It took a long time to establish this network and secure the necessary approvals, but we are now one of the few networks in the world that can eassily move data from a production hospital environment to a research network (while maintaining appropriate levels of anonymization and security).

What is the impact on institutional resources that form infrastructure?

Becuase of the complex nature of our network, we are regularly consulted by our campus Information Technology group, and our Library Services Division, on how we maintain data integrity and how we support the dissemination of our research. We have been helping them implement better infrastructure to support campus research.

What is the impact on information resources that form infrastructure?
Nothing to report.

What is the impact on technology transfer?

We have been actively trying to commercialize the technology through our commercial spinoff, Biosignal Analytics, Inc., and by directly marketing the technology to leading EEG equipment providers. Unfortunately, as mentioned previously, these efforts were not successful, so we have released the technology as open source.

We filed a patent on the core technology and have been working through the patent award process. We are in the final stages of discussions with the USPTO. Hopefully the patent will be awarded in 2022.

What is the impact on society beyond science and technology?
Nothing to report.

What percentage of the award's budget was spent in a foreign country?
Nothing to report.

Changes/Problems

Changes in approach and reason for change
Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

Obviously, COVID-19 has had an impact on this project. We juggled personnel and minimized exposure of students to the hospital environment. PI Picone served as an intermediary and visited the hospital after hours to collect data.

Changes that have a significant impact on expenditures
Nothing to report.

Significant changes in use or care of human subjects
Nothing to report.

Significant changes in use or care of vertebrate animals
Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.

Change in primary performance site location
Nothing to report.

Special Requirements

Responses to any special reporting requirements specified in the award terms and conditions, as well as any award specific reporting requirements.