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Introducing Neuroscience to High School Students through Low-Cost Brain Computer Interface Technologies

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Abstract:

Advancing an interest and literacy in Science Technology Engineering and Mathematics (STEM) fields in high school students through summer and after school programs has been widely popular since the 1990’s, and these programs are effective at improving retention and persistence after graduation. However, there still remains a lack of designing programs to increase interest and literacy of biomedical engineering (BME) related applications that are scalable at other institutions. This is typically due to the challenges of providing costly resources that are available only in specific laboratory settings and require graduate level expertise to operate. To provide a low-cost and scalable approach to introduce BME applications to high school students, the authors developed a BME high school summer program that was piloted in the summer of 2019. Aimed at introducing students to the BME field, the program focused on introducing neuroscience and neuroengineering principles using low-cost and open source materials.

The California State Summer School for Mathematics and Science (COSMOS) program “BioEngineering Your Brain: Controlling the World with Your Brainwaves” introduced basic neuroscience and bioengineering concepts to 24 high school students through lecture based material, in class assignments and activities, and hands-on laboratory projects. Through the use of low-cost and open source electroencephalography (EEG) devices (OpenBCI, Brooklyn, NY), students utilized a brain-computer interface (BCI) system to learn how to analyze brain data, characterize underlying physiological behaviors, and use algorithms to interface with a computer screen. The BCI system utilized steady state visual evoked potentials (SSVEP) of EEG to control a character in a maze on a computer screen. The cost of the system was < $300, and all materials are reusable for future program offerings. In addition, the signal processing techniques introduced students to Matlab Software (MathWorks, Natick, MA), which they learned how to use via the free Octave Online web user interface. Students were asked to develop a hypothesis, methods protocol, and validation protocol to determine how to optimize the BCI system in the laboratory. To provide instructional guidance, supplemental lectures and in class activities on brain physiology, programming and signal processing principles, brain recording modalities, as

well as BCI development and applications were provided throughout the program. To determine whether the program increased interest and confidence in pursuing BME as an undergraduate degree, an exit survey was provided to all students who attended the program.

The exit survey results showed that the program improved students' perceptions of BME and their interest in entering BME as an undergraduate major. In particular, 83.33% of the students agreed or strongly agreed that the experience increased their interest in studying BME, and 83.33% of the students agreed or strongly agreed that it increased their interest in the field of neuroscience. Furthermore, 87.5% of the students reported that the program increased their interest in pursuing scientific research as a career, and 91.67% of the students reported that it increased their interest in obtaining a graduate degree.

With advancements in hardware and open source software, the authors were able to develop a novel low-cost approach for introducing neuroscience, BME, and BCIs to high school students. Future work will expand the program to other BCI applications and developing online lecture modules that complement the laboratory portion of the program. In addition, the authors plan to introduce the program to other summer programs to assess its scalability and efficacy at improving interest and literacy of BME and neuroengineering principles to high school students. The authors will also introduce the program into our current undergraduate curriculum as part of a project that will be conducted alongside our current EEG experimental laboratory during the next year, as it will reinforce principles learned during the existing course content and provide a BME application of the laboratory.

Introduction:

Advancing an interest and literacy in Science Technology Engineering and Mathematics (STEM) fields in high school students through summer and after school programs has been widely popular since the 1990's, and these programs are effective at improving retention and persistence after graduation [1]. These initiatives have been implemented at both the national and statewide level to develop an awareness of engineering in women and minority populations [2, 3, 4]. Previous summer camps that focus on science and engineering have been very successful in enhancing student recruitment, an understanding of the field, and motivation to pursue an engineering degree [5].

However, there remains a lack of programs to increase interest and literacy of biomedical engineering (BME) related applications that are scalable at other institutions [6, 7]. This is typically due to the challenges of providing costly resources that are available only in specific laboratory settings and require graduate level expertise to operate. For instance, most summer camps that focus on engineering disciplines typically cover several disciplines across a few weeks or only devote one single day to cover each engineering branch [8, 9, 10]. Furthermore, BME specific programs typically encompass the entire multidisciplinary field, which requires implementation of a wide variety of projects [11, 12].

To provide a low-cost and scalable approach to introduce BME applications to high school students, the authors developed a BME high school summer program that was piloted in the summer of 2019. Aimed at introducing students to the BME field, the program focused on introducing neuroscience and neuroengineering principles using low-cost and open source materials.

Objective:

To determine the efficacy of this approach, the following research questions were posed:

1) Is it feasible to introduce high school students to the field of BME for neuroscience applications using low-cost approaches?

2) After completing the program, are students more interested in the field of BME and neuroscience?

3) After completing the program, are students more interested in pursuing graduate school and scientific research as a career?

These research questions have signification implications for future high school programs focused on introducing BME and neuroscience principles to high school students to foster interest in STEM and higher education. To this end, the summer program was evaluated using student surveys that were taken during the last day of the program. Additionally, student, faculty and teaching staff surveys and interviews were completed to assess the positive and negative aspects of the program. These were used to help define improvements for future offerings of the program.

Methods:

The Program Structure:

The summer California State Summer School for Math and Science (COSMOS) program at an R1 (highest research level) institution provides an intensive learning and discovery environment in a four-week high school residential program on the UCI campus. The program is taught by University of California, Irvine (UCI) faculty and their colleagues in higher education with the mission to motivate and encourage students interested in math and science to explore STEM topics and support college and career goals in STEM. Students are admitted after considering the following: gender, low socioeconomic status, underrepresented ethnic minorities, first generation college-bound, prior experiences, and statement of interest. The students who applied for the cluster entitled “BioEngineering Your Brain: Controlling the World with Your Brainwaves” were also required to have taken high school biology and computer literacy prior to admission into the program. In addition, other students that applied for the COSMOS program were admitted among the nine clusters with a variety of engineering and STEM discipline topics and prerequisites. These other cluster topics included pharmaceutical sciences and cell biology, computation and machine learning, mathematical modeling of biologic systems, chemistry, computer science and human computer interaction, clinical trials design, developmental and cell biology, and civil and environmental engineering.

After admission into the program, 24 high school students were enrolled in July of 2019 and completed the 4-week summer program. The program focused on introducing basic neuroscience and bioengineering concepts through lecture-based material, in class assignments and activities, and hands-on laboratory projects. Specifically, the program included three-hour lectures three times per week, 5.5-hour intensive laboratory exercises two times per week, three-hour scientific method training lectures and exercises two times per week, and 2.5-hour distinguished lectures once per week. Table 1 below shows the weekly training schedule that the students followed throughout the course of the program.

Table 1: Weekly schedule for students in the program.

Week					
	Monday	Tuesday	Wednesday	Thursday	Friday
7:00am – 8:30am	Breakfast, walk to class				
9:00am	Lecture	Laboratory	Lecture	Laboratory	Lecture
10:00am					
11:00am					
12:00pm	Lunch				
1:00pm	Scientific Method Lecture	Laboratory	Distinguished Lecture Series	Laboratory	Scientific Method Lecture
2:00pm					
3:00pm					
4:00pm					
5:00pm – 10:00pm	Free time on campus, dinner, study and project development				

During the laboratory and lecture portions of the program, students were introduced to neuroscience and bioengineering principles by learning how to develop and use brain-computer interface (BCI) systems for various applications. This included the following student learning outcomes:

1. Understand basic brain physiology
2. Understand brain imaging modalities and their applications
3. Identify and analyze electroencephalogram (EEG) data
4. Use programming concepts to analyze physiological data
5. Utilize EEG signals to recognize physiological behaviors in real time
6. Detect physiological behaviors using time-based and frequency-based analyses
7. Learn how BCIs can be applied to different applications, including communication, prosthetics, rehabilitation, games, neurofeedback attention, and mental workload
8. Optimize BCIs using controlled experimentation and the scientific method given real time considerations

The lecture-based modules provided interactive lectures and in class assignments that guided students through basic neuroscience and coding principles. Through the use of portable whiteboards, students were asked to work in small groups to learn basic programming techniques, develop algorithms for analysis and classification of EEG data, perform experimental design for different neuroscience applications, and learn how to identify EEG artifacts and underlying brain signals using frequency analysis. The whiteboards were used during the in class assignments and group work as whiteboarding learning modules align with effective problem based and active learning strategies [13].

After completion of the four week program, the students presented their scientific studies using their findings from the laboratory portion of the course. As described below, students were trained during the scientific method portion of the program (Table 1) to understand how to develop a hypothesis, perform background research regarding their hypothesis, perform experimentation on their hypothesis in a controlled study during their laboratory modules, analyze their data, and develop conclusions based on their findings. Their findings were then presented in an end-of-program poster session where they disseminated their findings and experiences to instructors, students, and family members.

Development of BCI Laboratory Modules:

Through the use of low-cost and open source electroencephalography (EEG) devices (OpenBCI, Brooklyn, NY), students utilized a brain-computer interface (BCI) system to learn how to analyze brain data, characterize underlying physiological behaviors, and use algorithms to interface with a computer program. The BCI system utilized steady state visual evoked potentials (SSVEP) of EEG to control a character in a maze on a computer screen. The cost of the system was < $300, and all materials are reusable for future program offerings. In addition, the signal processing techniques introduced students to Matlab Software (MathWorks, Natick, MA), which they learned how to use via the free Octave Online web user interface.

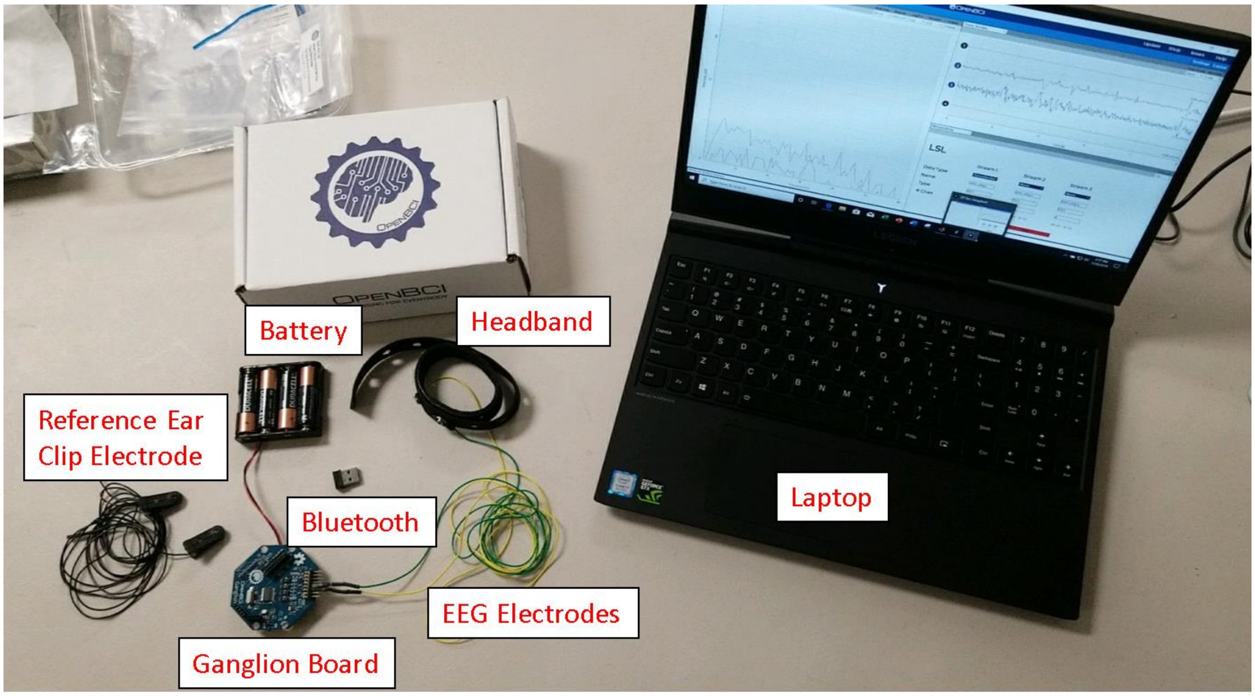

Figure 1: Image of the BCI system set up and interface, including the OpenBCI EEG toolkit and laptop required to run the BCI system and OpenBCI data acquisition software.

Six OpenBCI systems and laptops were provided to the students, resulting in teams of four students. The following cost breakdown was used to provide laboratory equipment to the students (Table 2). Excluding the cost of a laptop (the majority of students already had access to personal laptops), the entire cost of the BCI system for each group was $282. All software was provided as open access and free software, allowing students to be able to use their own computers to operate the BCI system. In addition to the required hardware, necessary soft materials included alcohol wipes for disinfecting between participants for sterilization, as well as summer stipend for the two student laboratory instructors who led this portion of the program.

Table 2: Cost breakdown of the BCI system used during the laboratory assignments and program project.

Item	Cost
OpenBCI Control Board	$200
Bluetooth Dongle	$12
Headband and Electrodes	$70
Laptops	$640
Total	**$922**

The BCI systems were set up and used in three parts: a 10 minute training session, classification of the EEG signal into four classes (left, right, up and down), and a real-time performance of the BCI using a simple maze. In general, a traditional BCI system records brain signals, typically using EEG, the signals are sent in real time to a computer to preform frequency-based signal processing and classification, and the classification of each trial is translated into a control signal to control an end effector that provides real time feedback to the user (Figure 2). In order to accomplish this, a training session is first performed in which EEG data is obtained “offline” (with no end effector feedback) with known labels to create a classifier that distinguishes between the EEG signals in each class. In the case of the maze, these signals were generated by having students focus on four square boxes that flashed at set frequencies ranging from 2-20 Hz, depending on the students’ hypothesized optimal frequency values (Figure 3). Using the Fast Fourier Transform (FFT), an increase in power spectral density can be observed at the frequency that the user is attending; this response will be maximal in the EEG channels over the occipital lobe. This is known as the SSVEP, a natural response to visual stimulation at specific frequencies when the retina is excited by a visual stimulus [14], and it has been widely used in BCI research. Once a classifier is generated using the training data, the user is then able to control the character in a simple maze in real time by attending to the desired direction of movement (i.e. left, right, up, or down). The students were tasked with determining optimal frequencies, EEG electrode locations, stimulus color, and other experimental variables such as algorithm design and processing techniques. Their goal was to complete the maze as quickly as possible in real time. This module enabled students to perform several different potential experimental designs in their scientific study to optimize the BCI system for real time control.

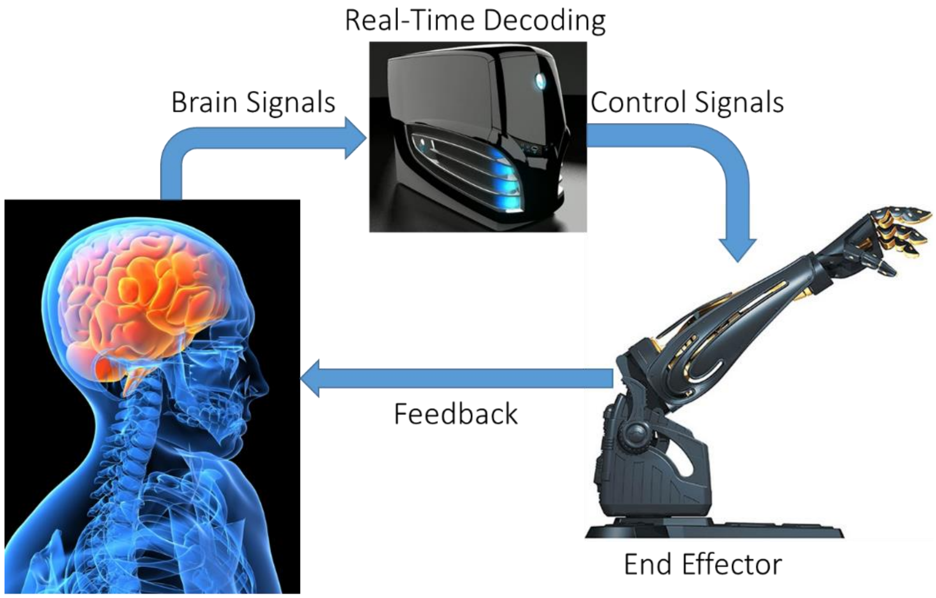

Figure 2: Overview of a BCI system for real time control.

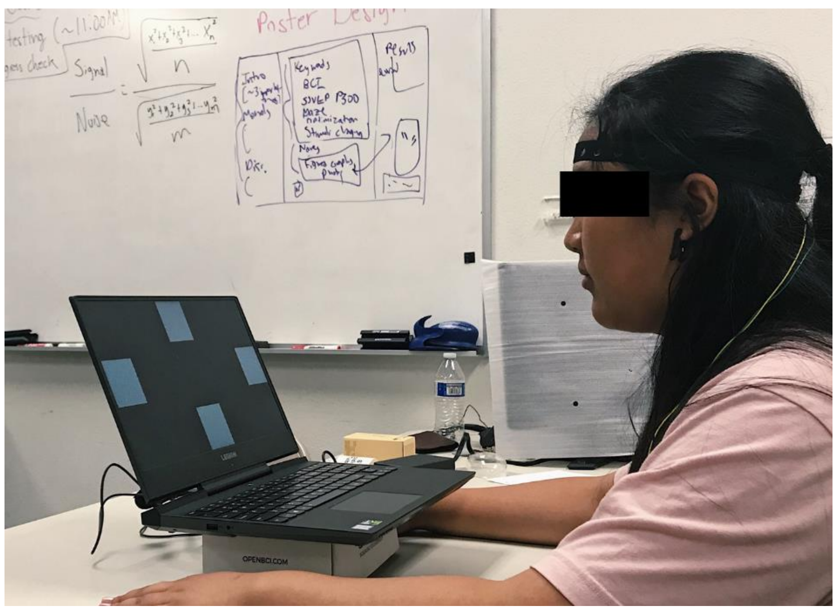

Figure 3: Student participant performing the offline training session of the BCI system. Four distinct SSVEP responses were measured using EEG by having the user focus on flashing squares at four distinct frequencies.

Student Project using the Scientific Method:

Students were asked to develop a hypothesis, methods protocol, and validation protocol to determine how to optimize the BCI system in the laboratory. To provide instructional guidance, supplemental lectures and in class activities on brain physiology, programming and signal processing principles, brain recording modalities, as well as BCI development and applications were provided throughout the program. In addition, students were guided by other instructors during their Scientific Methods Lecture (Table 1) on how to perform a literature review of current research, formulate a hypothesis, create a controlled study design, how to document their study and experimentation, and how to draw conclusions based upon the results of their findings. Students then disseminated their findings through a scientific poster, which they designed during the Scientific Methods Lecture module and the laboratory portion of the course. Sample scientific posters from undergraduate and graduate research on BCIs were provided to show how to appropriately disseminate research findings at a scientific conference. In one study, the students analyzed the effect of stimulus size, represented by the square images that were used to elicit SSVEP in the EEG. They recorded the classification accuracy and error rate of the training sessions as the stimulus size varied. They controlled the algorithm design, EEG electrode locations, and all other settings to determine which pixel size had the highest classification accuracy and comfort level as reported by each subject. They found that medium-sized stimuli resulted in the highest classification accuracy; however, the smallest-sized stimuli produced the highest comfort for the individuals, as it allowed subjects to more easily focus on the desired stimuli while all other stimuli were being presented.

Data Collection:

To determine whether the program increased interest and confidence in pursuing an undergraduate BME degree, an exit survey was provided to all students who attended the program. All 24 students who were enrolled in the program completed the exit survey during the last week of the course. The post-program survey, detailed in the section below, was then analyzed both quantitatively and qualitatively to assess whether the students became more interested in BME, neuroscience, and pursuing graduate school as a career.

In addition to the post-program survey, interviews were also conducted with the instructors and teaching staff to assess the feasibility of the laboratory modules and lectures on BME and neuroscience topics. To this end, the following questions were posed:

1. Was the BCI Laboratory module feasible to perform throughout the program?
2. What did you like about the program “BioEngineering Your Brain: Controlling the World with Your Brainwaves”?
3. What did you not like about the program “BioEngineering Your Brain: Controlling the World with Your Brainwaves”?
4. What would you do the same if you were to instruct the program “BioEngineering Your Brain: Controlling the World with Your Brainwaves” next year?
5. What would you do differently if you were to instruct the program “BioEngineering Your Brain: Controlling the World with Your Brainwaves” next year?
6. What BME, research, and neuroscience concepts were the students able to understand by the end of the program?
7. What BME, research, and neuroscience concepts did the students struggle to understand by the end of the program?

Post-Program Survey:

To assess student interest in BME and neuroscience, as well as their interest in pursuing graduate school and scientific research as a career, a post-program survey was distributed to the students. As presented in Table 3, the following constructs were examined.

Table 3: Constructs and resulting survey questions to assess students' level of interest in BME, neuroscience, and pursuing a career in scientific research.

Construct	**Question**
Demographics	In Fall 2019, what year of high school will you begin?
	What is your gender?
	Are you White, Black or African-American, American Indian or Alaskan Native, Asian, Native Hawaiian or other Pacific Islander, or some other race?
	Are you Spanish, Hispanic or Latino origin or descent?
	If you attend college, will you consider yourself to be a first generation college student?
Educational Background	If you have taken the SAT exam in preparation for college applications, what was your approximate score on the exam?
	I have participated (or am currently participating) in the following AP classes.
	My approximate unweighted GPA is:
Interest in College, Graduate School, Engineering, BME, Neuroscience, or Scientific Research	Participating in the program has increased the likelihood that I will go to college.
	Participating in the program has increased my interest in obtaining a graduate degree (MS, PhD, MD).
	Participating in the program has increased my interest in studying engineering.
	Participating in the program has increased my interest in studying BME.
	Participating in the program has increased my interest in studying neuroscience.
	Participating in the program has increased my interest in doing scientific research.
Improvement of confidence and understanding of science and engineering	The program has helped me feel more confident about my ability to pursue engineering.
	The program has helped me feel more confident about my ability to pursue science.
	The program has helped me feel more confident about my ability to do computer programming.
	The program has helped me feel more confident about my ability to record and analyze data.

	The program has helped me understand options for further education in science and engineering.
	The program has helped me understand options for future careers in science and engineering.
Perceptions of the program	Please write three words or short phrases that best describe your experience in the program.
	Which aspects of the program did you like the most?
	Which aspects of the program did you like the least?
	List any specific suggestions you have for improving the program for next year.

As seen in Table 3, students' perceptions of the summer program were ascertained using both categorical items (e.g. "yes" or "no" or Likert scales) and open-ended questions. The categorical and Likert scaled questions were quantitatively analyzed to assess the level of student interest in the field of BME, neuroscience, and pursuing scientific research as a career. In addition, both the positive and negative aspects of the program were qualitatively examined, as well as the potential improvements that can be made. This helped determine which activities of the summer program led to a better understanding of neuroscience and BME principles, and which activities increased their interest in pursuing engineering and graduate school.

Results:

Quantitative Analysis of Post-Program Student Surveys:

It was found that all 24 students completed the post-program survey. Their demographic data is presented in Table 2 below. The exit survey results showed that the program improved students' perceptions of BME and their interest in entering BME as an undergraduate major. In particular, 83.33% of the students agreed or strongly agreed that the experience increased their interest in studying BME, and 83.33% of the students agreed or strongly agreed that it increased their interest in the field of neuroscience. Furthermore, 87.5% of the students reported that the program increased their interest in pursuing scientific research as a career, and 91.67% of the students reported that it increased their interest in obtaining a graduate degree.

Table 2: Demographics of the study participants who completed the post-course online survey.

Number of Participants: 24			
Year in High School	Sophomore	Junior	Senior
	12.50% (3)	45.83% (11)	41.67% (10)
First Generation	8.33% (2)		
Female	45.83% (11)		
Hispanic	0.00% (0)		
Asian American	79.17% (19)		
Overall GPA	3.5-4.0	> 4.0	
	91.67% (22)	8.33% (2)	

Qualitative Assessment of Post-Program Student Surveys:

After qualitatively analyzing the post-course survey, it was found that many students reported that the program increased their interest in neuroscience, BME, and the possibility of pursuing a scientific research career. The comments on the positive and negative aspects of the program were overwhelmingly positive. For instance, students reported that:

"I enjoyed working with the BCI technology and optimizing it since it's the first that I have seen of its kind."

"I enjoyed how we learned applications of neuroscience to biomedical engineering. I had previously had lots of experience with neuroscience but had never applied that knowledge to engineering."

"I loved learning more about how to program with MATLAB and work with EEG software. Additionally, it was cool to learn more about the fields of biomedical engineering and neuroscience, and I enjoyed working with the professors on our projects."

"The professors and TAs were amazing and wanted to see us succeed. I learned much about engineering and computer programming that opened up more career possibilities for me."

"I liked that cluster 7 consisted of dry labs only, as they were much easier to work with. I also like the "challenge" factor of trying to get out OpenBCI kit properly functioning. I also liked that we got to hear the stories about others who have invested their life in neuroscience and biomedical engineering."

"I enjoyed gaining more insight into what happens in a computer programming based research lab. In addition, I was able to learn more about the field of BME, and, as a rising senior, it definitely made me consider majoring in BME in college."

"Much of the instruction regarding specifically neuroscience and the brain was fascinating. The opportunities to listen to and speak with professors and other students was also extremely insightful and greatly influenced how I view my future path in academics."

"I really enjoyed doing hands-on projects in the lab with BCIs and I found the guest speakers on Wednesday (7/31/19) really interesting, insightful and helpful. I enjoyed the talk with the panel of students as well. The lectures were also helpful in that they explained a lot of new concepts in a digestible way."

"I loved learning about the anatomy and the functions of our brain. I came into class looking forward to all the lecture (I seriously mean it!). I also really enjoyed learning how to apply the knowledge we learned to real life situations."

These comments highlight the importance of linking real-world applications of BME to basic math and biology principles. Students found that the laboratory modules and lectures complimented the basic neuroscience and computer engineering principles that they had learned in their high school courses. Specifically, 66.67% (16) of the students had taken Advanced Placement (AP) Biology as well as AP Calculus in their high schools. The lecture activities and laboratories used principles from these courses and showed how they can be applied to biomedical applications of neuroscience. For instance, students learned how to transform signals into the frequency domain using the Fourier Transform, a powerful technique used in BME for physiological signal analysis. To teach this, the instructors provided lecture activities (see Appendix A) that demonstrated how the dot product taught in AP Calculus can be used to assess the frequencies underlying a brain signal from EEG. This was then supplemented with laboratory modules that required students to develop a Matlab algorithm that uses the Fourier transform to decompose the EEG signals into the frequency domain. Students then used this information to predict which stimuli their subject was attending to in order to control the BCI maze.

To relate neurons and their action potentials, a topic taught in AP Biology courses, to the voltage differences measured with EEG (with different areas of the brain corresponding to physiological behaviors), lecture activities focused on students using their knowledge of anatomy to predict specific physiological behaviors from an EEG signal (see Appendix B). For example, students were shown EEG and the corresponding power spectral data for electrodes placed on different portions of the brain; based on the anatomical location alone, the students had to determine whether the signal was due to upper extremity movement, lower extremity movement, or a visual stimulus. This information was then used in their laboratory modules to identify the appropriate electrode locations to optimize the BCI Maze, given that it relied on a visually-evoked SSVEP response.

Analysis of Post-Program Teaching Staff and Instructor Interviews:

The faculty and teaching staff interviews were also qualitatively analyzed to assess the feasibility of the laboratory modules and lectures. The teaching staff and instructors perceived the BCI course as a feasible task for high school students to perform and understand. In particular, the teaching staff noted that students were able to understand the practical benefits and useful applications of engineering, as well as how signal processing, frequency analysis, and basic physiology of the human brain can guide researchers to develop practical BME applications for neuroscience. They also noted that through close interaction with the students, the students were able to understand how use of the scientific method can provide different solutions and methods to optimize the BCI system. Through the use of a scaled approach to understanding how to develop a BCI system, the teaching staff noted that this technique helped students use what they learned in lecture to better develop a working BCI system in their laboratory modules. In particular, the teaching staff and instructors noted that:

"The BCI lab module was feasible to perform, but difficult to access due to troubleshooting with the device. This was particularly apparent at the earlier weeks where the devices would not work well together in a room."

"The module was feasible, and the students not only learned how to operate and program the BCI, but they learned the basic principles behind its operation. For example, why do we need to record from a specific location on the head? What do EEG signals look like and why? Several students commented to me that they valued this aspect of the program."

"It was nice to see students that were very driven and enthusiastic as well. This was particularly challenging and interesting with student groups that were interested in deviating from the

original project. Interacting with students also taught us different ways to go about our own projects, as well improve communication with them."

"Having intermediate steps such as alpha rhythm, artefact, etc. was nice since it warmed students up to the study as well as let them use what they learned in MATLAB."

Despite the success of the program, the teaching staff and instructors noted several challenges, given the high level of knowledge required for high school students to understand concepts of research, BME, and neuroscience. For instance, the teaching staff noted that students struggled to understand the degree of openness and troubleshooting that is required for practical BME applications. Specifically, the teaching staff mentioned in their interviews that students did not understand that *"research is not straightforward, and there is no "right" answers at the end"*, and that *"troubleshooting and repeating tasks <may be> "unfun", but it is very common in research"*. The instructors also noted this missing perception of common practices and challenges seen in performing research. For example, one instructor mentioned that:

"...students were all surprised at how difficult it was to train their classifier and run the BCI, even when they had the correct hardware and software. Sometimes, their device just did not work, and the students had to trouble-shoot it. We emphasized to the students that this was a normal part of research because you are attempting to do something no one has ever done before. It's very different than doing a homework problem that you know has a correct answer, and I think this made a big impression on the students."

These issues reflect the underlying challenges and misconceptions of the scientific method for students who are new to research. Because students are typically given close-ended problems in their high school courses, where there is a specific "right" answer, it is difficult for them to understand that most real life applications of engineering and science are open-ended and that multiple solutions can produce the same result. This has been evident in prior research [15], showing that restricted lab procedures in high schools frequently result in moderate learning processes, as students do not spend adequate time in sense-making (i.e. making sense of or giving meaning to developments and experiences).

Discussion:

The results of the study indicate that it is feasible to introduce high school students to BME and neuroscience applications using low-cost BCI systems. In particular, the total equipment cost of a BCI module (including a laptop) was $922, and all equipment is portable, allowing students to work in any location on campus to perform experiments. Furthermore, the instructional team interviews found that the BCI maze game and potential experimental studies presented to the students were feasible to perform within the 4 weeks of the summer program. The use of supplemental lectures, activities, and laboratory modules allowed students to be able to understand basic neuroscience and engineering principles required for BME applications. In particular, both the students and instructional team found that the practical applications of BME presented during the lectures and in the laboratory modules allowed students to have a deeper understanding of how to use their knowledge of biology, mathematics, and computer programming to develop optimal solutions for the BCI system using the scientific method. This allowed the students to develop a deeper knowledge of practical neuroscience and BME applications, and to see how basic science principles can lead to the development of real-world solutions for healthcare problems.

The results of the student survey demonstrated that the program improved students' perceptions of BME and increased their interest in pursuing this discipline as an undergraduate major. The majority of students also stated that the program increased their interest in neuroscience. In particular, the results of the qualitative analysis highlight the importance of integrating basic principles from high school courses into higher BME and neuroscience topics while linking these principles to real-world applications. *Due to the mathematical knowledge required to understand the Fast Fourier Transform, an important concept in the understanding of neural engineering, concepts such as the dot product were explained during the formal lectures both graphically and mathematically (see Appendix A). By incorporating the basic principles regarding the mathematical knowledge required to understand frequency decomposition both in lecture and through programming during the laboratory sessions, students were able to learn about these fundamentals without requiring a prerequisite of AP Calculus.*

Through in class activities and lectures by the instructional team and those in the field, students gained knowledge that they were able to apply to a real-world application of BCIs in the laboratory modules. This structured learning approach allowed the students to use lower cognitive processes of the revised Bloom's taxonomy to generate, plan, and produce novel solutions from an existing ones by optimizing the BCI maze [16]. Furthermore, the student survey results highlight the importance of having an instructional team with positive teacher attitudes and high self-efficacy about the fields of BME and neuroscience, as it has a strong positive effect on the teaching and learning processes in these fields [17]. This was highlighted in several comments from the students, as it positively affected their interest in pursuing these fields during their undergraduate careers.

Despite the overwhelming success of the program, several revisions will be made in future offerings of the summer program to be able to improve upon the scalability and accessibility to a broader range of student audiences. For example, future program offerings will focus on recruiting more low-income, first generation, and underrepresented minority students. It can be seen from the student demographics in Table 2 that most students who participated in the program were demographically privileged. This was due to the demographic makeup of the application pool of the entire COSMOS program. Thus, recruitment strategies must be improved to allow for more low-income, first generation, and underrepresented minorities to become aware and given the opportunity to participate in the program at low cost. The instructors are making an effort to recruit these individuals by revising the prerequisites of biology and computer literacy courses to equivalent courses that are available at representative schools with these student populations.

In addition to improving student recruitment strategies, the program structure will also be changed so that students will form teams based on their prior knowledge of required topics such as computer programming, neuroscience, and mathematics rather than self-formation of teams in the beginning of the laboratory modules. This will ensure heterogeneous team structure and will facilitate more peer learning [18]. In addition, once teams are formed, we plan to provide laboratory modules and complementary online lecture modules during the first two weeks of the program that require students to program specific modules of the BCI system rather than providing them with a completed system that requires optimization. We hope that this will give students a deeper understanding of the basic concepts needed to develop a BCI device as well as more ownership over their own project and experimental study. Finally, once these improvements are made, we plan to assess the scalability of our program's approach by implementing it in other high school summer programs and our own current undergraduate curriculum's experimental laboratory. This will help us determine whether this learning experience reinforces scientific and engineering principles and increases student interest in BME and neuroscience fields as a potential career.

Conclusion:

In summary, with advancements in hardware and open source software, the authors were able to develop a novel low-cost approach for introducing neuroscience, BME, and BCIs to high school students. Future work will expand the program to include better recruitment of students from a more diverse population to reach a broader range of audiences. In addition, we plan to expand our program to more in depth portions of the BCI system and applications of other BCI systems through developing online lecture modules and activities that complement the laboratory portion of the program. In addition, we plan to introduce the program to other summer programs to assess its scalability and efficacy at improving interest and literacy of BME and neuroengineering principles to high school students, particularly those from low-income and underrepresented communities. We will also introduce the program into our current undergraduate curriculum as part of a project that will be conducted alongside our current experimental laboratory during the next year; this will reinforce principles learned during the laboratory module and expose students to a real world BME application of the material.

Acknowledgements:

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Appendices:

Appendix A: Sample Lecture Activities that Utilized High School Science Principles

Transformation of Signals into Frequency Domain using Fourier Transform and the Dot Product:

How can we determine which sine waves make up a signal?

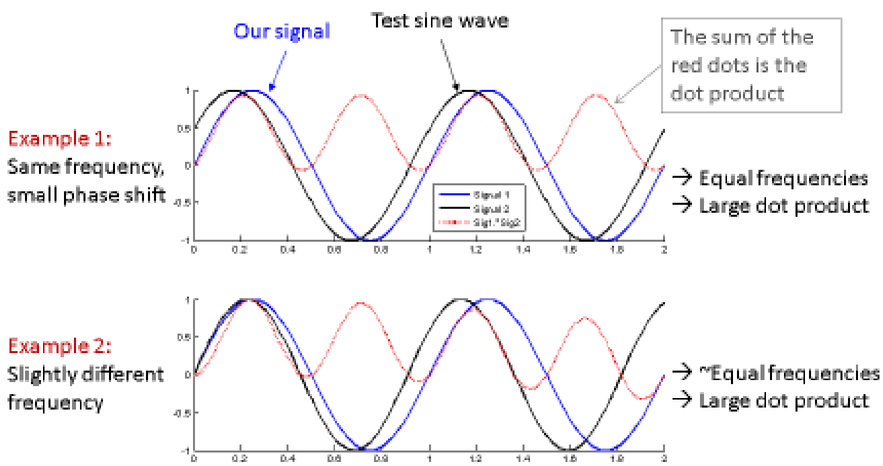
- Compare sine waves of different frequencies to our signal
- Sine waves that have the same frequency as our signal will give bigger values
- The amplitude of the result will be proportional to the amplitude of the frequency component

- We will do the comparison mathematically using the **dot product**:

```
>> a = [a1  a2 ... an]
>> b = [b1  b2  ... bn]
>> dotProduct = a1*b1 + a2*b2 + ... + an*bn
```

Decomposing a signal into frequencies

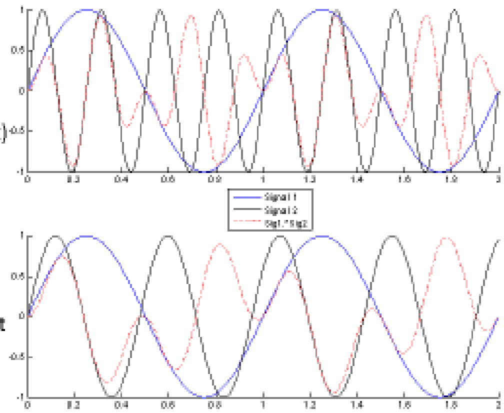
Intuition: The dot product of similar sine waves will be large



Decomposing a signal into frequencies

Intuition: The dot product of sine waves of different frequencies will be small.

Example 3:
Frequencies are multiples of one another (here 4x)



→ Frequencies do not match
→ Dot product ~= 0

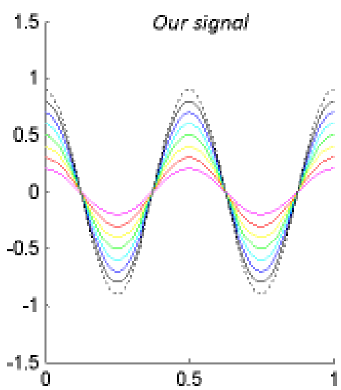
Example 4:
Frequencies are different, but not multiples

→ Frequencies do not match
→ Dot product ~= 0

Decomposing a signal into frequencies

How does the dot product vary with magnitude?

2 Hz sine wave dotted with 2Hz frequencies with a range of <u>amplitudes</u> equals…



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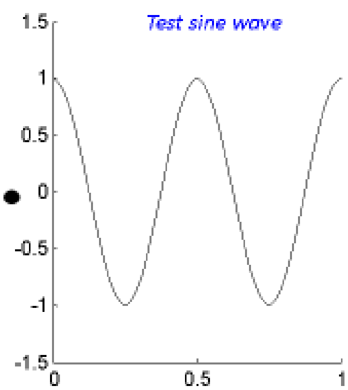


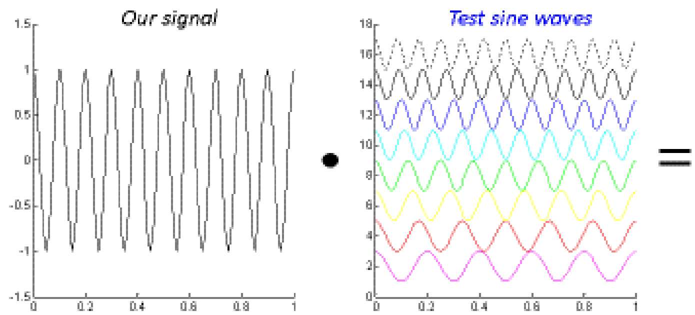
=

biggest
bigger
big
medium-big
medium
small
smaller
smallest

Decomposing a signal into frequencies

How does the dot product vary with frequency?

10 Hz sine wave dotted with frequencies ranging from 5 to 12 equals…



0
0
BIG
0
0
0
0
0

Decomposing a signal into frequencies

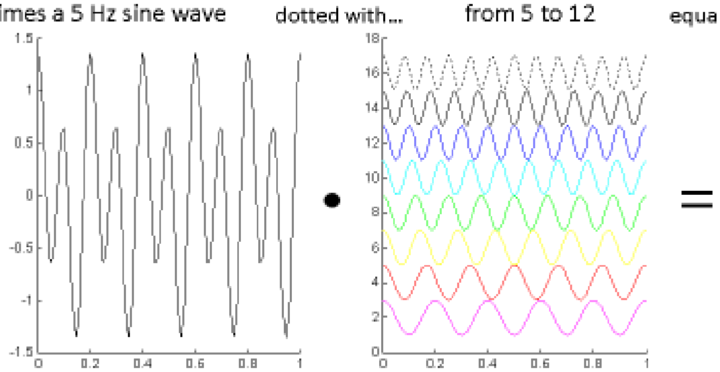
This also works with signals of mixed frequencies:

10 Hz sine wave
+ 0.5 times a 5 Hz sine wave

dotted with…

frequencies ranging
from 5 to 12

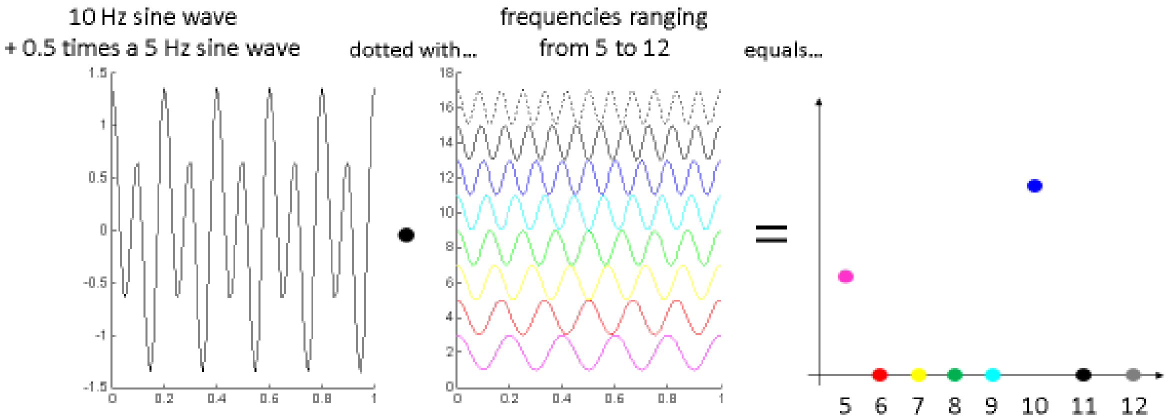
equals…



0 (12 Hz)
0 (11 Hz)
Big (10 Hz)
0 (9 Hz)
0 (8 Hz)
0 (7 Hz)
0 (6 Hz)
Medium (5 Hz)

Decomposing a signal into frequencies

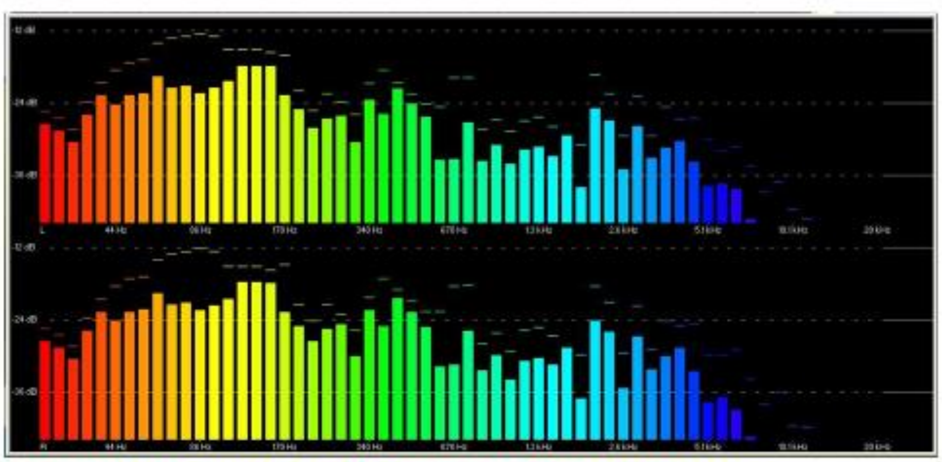
This also works with signals of mixed frequencies:



This procedure is the Fourier transform!

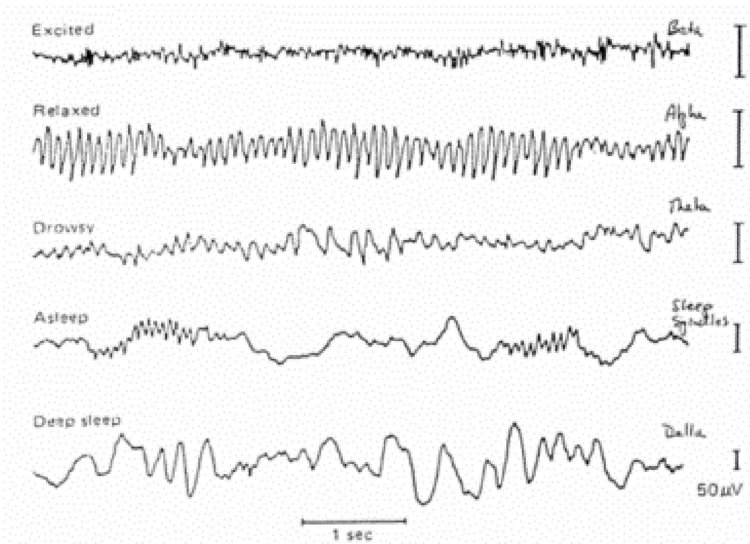
Example: Frequencies of sound

The equalizer shows the frequencies present in an audio signal:



All signals can be decomposed into a sum of sine waves.

Example: Frequencies of EEG



~20 Hz

~10 Hz

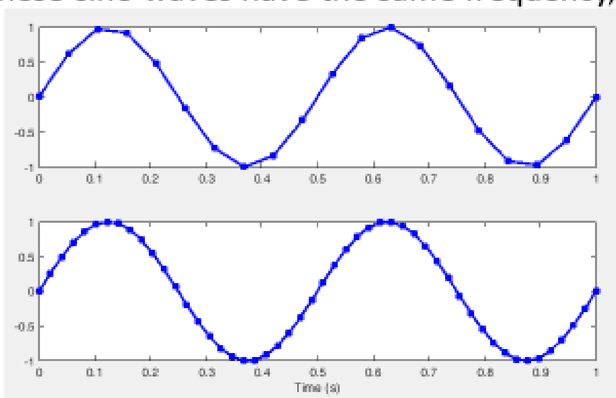
~4-7 Hz

~2 Hz + 13 Hz

~2 Hz + 5 Hz

What is sampling rate?

- The **sampling rate** is the number of measurements taken per second
- Units = Hertz (Hz); same units as frequency
- These sine waves have the same frequency, but different sampling rates:



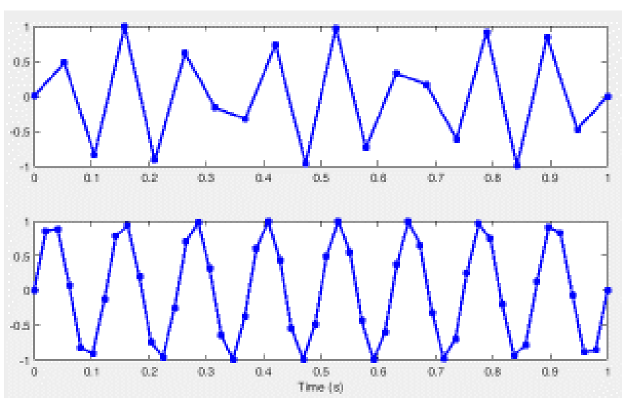
Sampling rate

20 samples per second = 20 Hz
(low sampling rate)

50 samples per second = 50 Hz
(high sampling rate)

What is sampling rate?

- In general, a higher sampling rate is always better
- Higher frequencies require higher sampling rates:

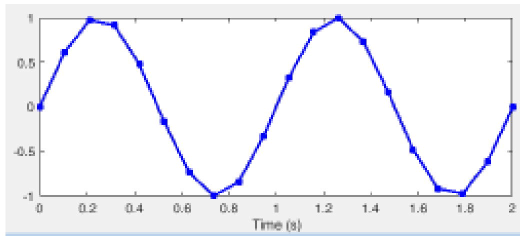


8 Hz sine wave with 20 Hz sampling rate

8 Hz sine wave with 50 Hz sampling rate

Whiteboard 1

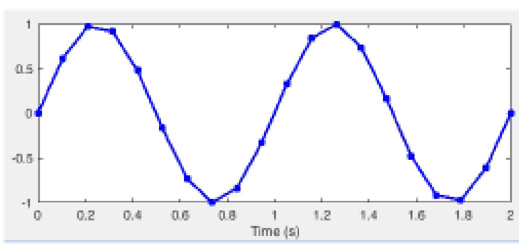
1. What are the frequency and sampling rate of this signal?



2. Write Matlab code to create a 5 Hz sine wave with a 25 Hz sampling rate that lasts 1 second.
3. Write Matlab code to create a 7 Hz sine wave with a 40 Hz sampling rate that lasts 2 seconds.

Whiteboard 1

1. What are the frequency and sampling rate of this signal?

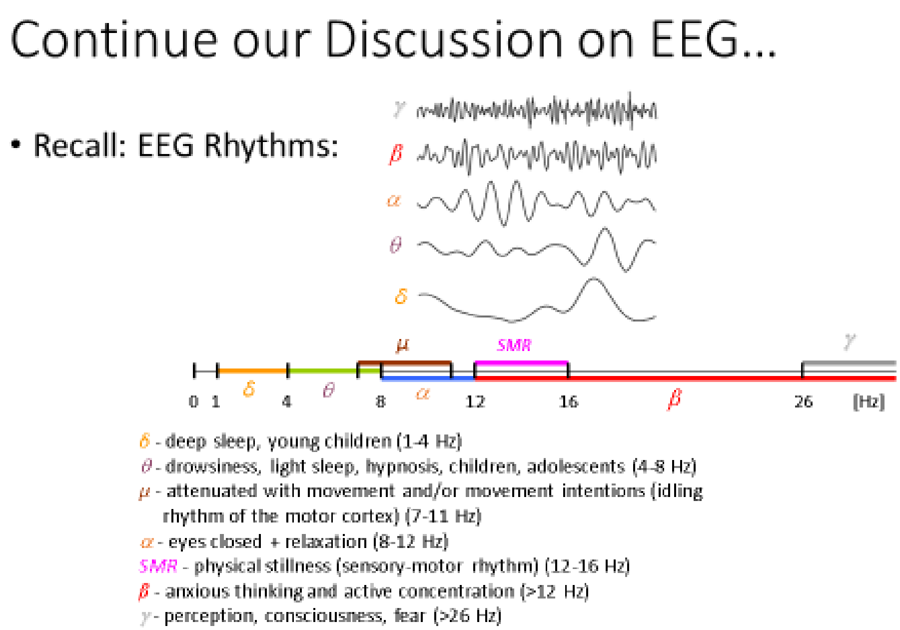


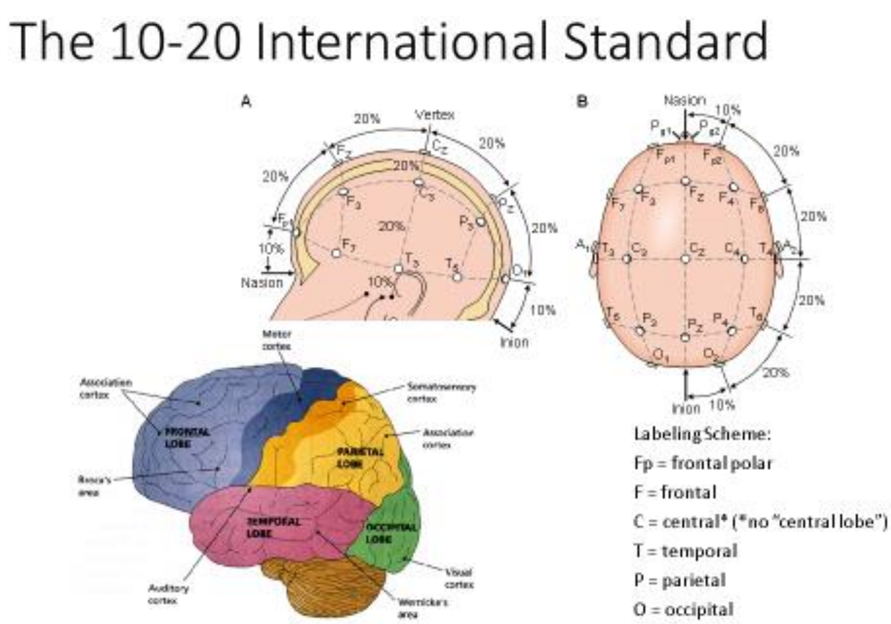
1 Hz sine wave with 10 Hz sampling rate

2. Write Matlab code to create a 5 Hz sine wave with a 25 Hz sampling rate that lasts 1 second.
3. Write Matlab code to create a 7 Hz sine wave with a 40 Hz sampling rate that lasts 2 seconds.

Appendix B: Sample Lecture Activities that Used High School Principles of Anatomy

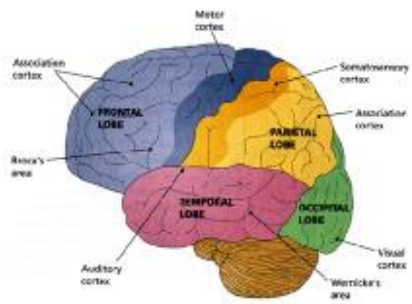
Using Anatomy to Predict Physiological Behaviors from an EEG Signal:





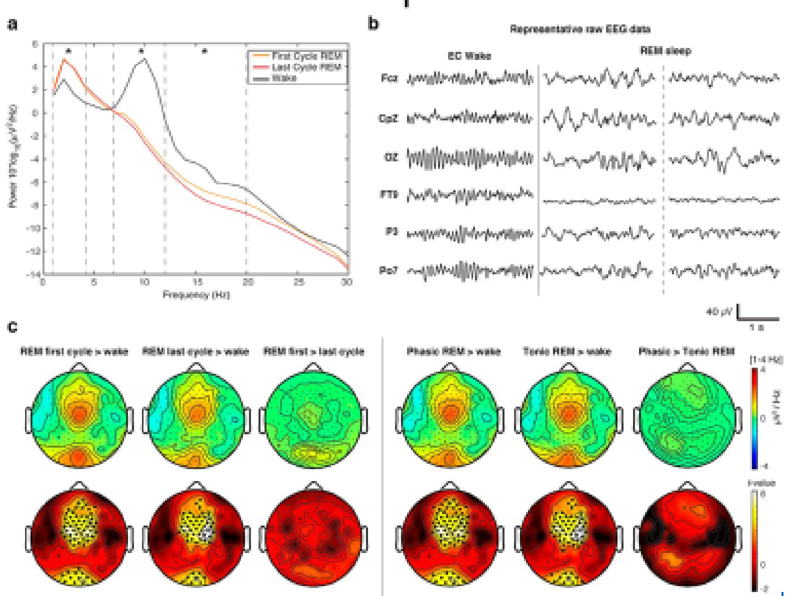
Activity: Label the EEG Electrodes on the Brain

- Label the location of the following electrodes on the surface of the brain
  - 1, 3, 5, 7 = left side
  - F, C, T, P, O = region of the brain



Labeling Scheme:
Fp = frontal polar
F = frontal
C = central* (*no "central lobe")
T = temporal
P = parietal
O = occipital

Power Spectrums of EEG: *Example*



Caption from Paper:

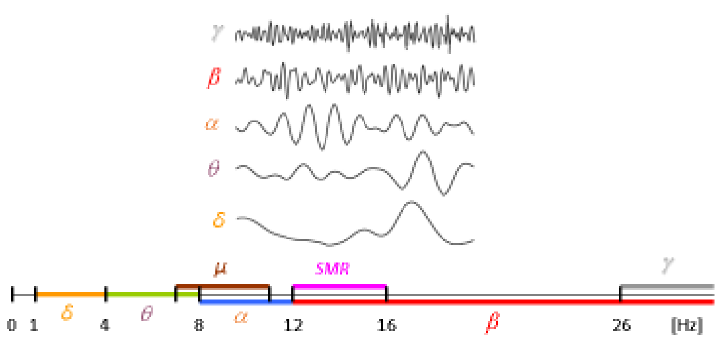
EEG topography of REM sleep contrasted with quiet wakefulness in θ, α and β frequency bands. Topographical differences in oscillatory power between the first cycle of REM sleep contrasted with wake (left panel), the last cycle of REM sleep contrasted with wake (central panel), and the first cycle of REM sleep contrasted with the last cycle of REM sleep (right panel) for θ (4–7 Hz), α (8–12 Hz), and β (12–20 Hz) frequency bands; t values are plotted for all electrodes (two-tailed, paired t test); white dots indicate significant differences between states ($p < 0.05$) after correcting for multiple comparisons with statistical nonparametric mapping (SNPM).

Source: Baird et al. eNeuro, 5 (4), 2018.
https://www.eneuro.org/content/5/4/ENEURO.0293-18.2018

Power Spectrums of EEG

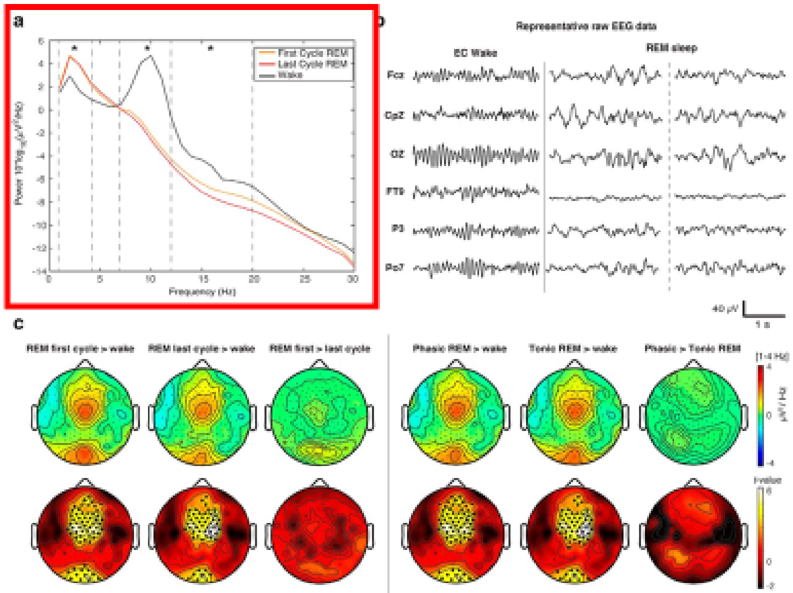
- EEG is very *noisy* so you will see lots of peaks over lots of frequencies
- We typically <u>compare</u> the power spectrum of a behavior to the lack of that same behavior to see if there is a difference at a particular frequency and channel location
- We can map the average power across specific frequency bands onto each channel to create a <u>topography map</u>

Recall: Characteristic EEG Rhythms



δ - deep sleep, young children (1-4 Hz)
θ - drowsiness, light sleep, hypnosis, children, adolescents (4-8 Hz)
μ - attenuated (reduced) with movement and/or movement intentions (idling rhythm of the motor cortex) (7-11 Hz)
α - eyes closed + relaxation (8-12 Hz)
SMR - physical stillness (sensory-motor rhythm) (12-16 Hz)
β - anxious thinking and active concentration (>12 Hz)
γ - perception, consciousness, fear (>26 Hz)

Interpreting Power Spectrums



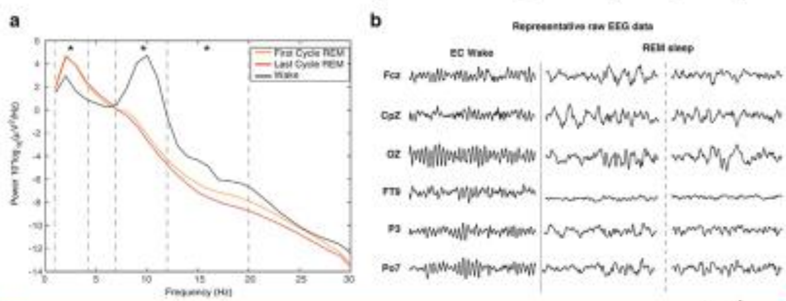
<u>Based on the Power Spectrum:</u>

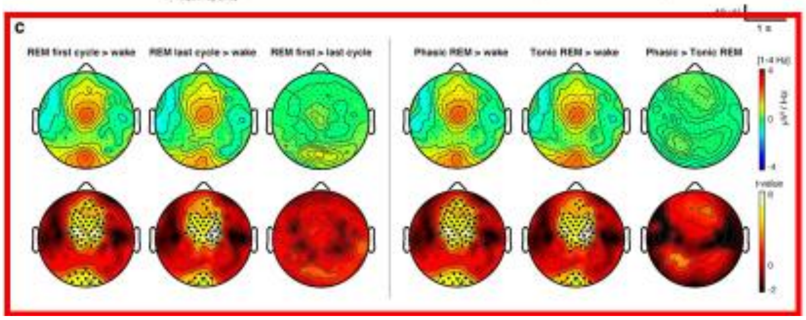
What are the most important frequencies when comparing awake vs. REM sleep?

δ - deep sleep, young children (1-4 Hz)
θ - drowsiness, light sleep, hypnosis, children, adolescents (4-8 Hz)
μ - attenuated (reduced) with movement and/or movement intentions (idling rhythm of the motor cortex) (7-11 Hz)
α - eyes closed + relaxation (8-12 Hz)
SMR - physical stillness (sensory-motor rhythm) (12-16 Hz)
β - anxious thinking and active concentration (>12 Hz)
γ - perception, consciousness, fear (>26 Hz)

Source: Baird et al. eNeuro, 5 (4), 2018.

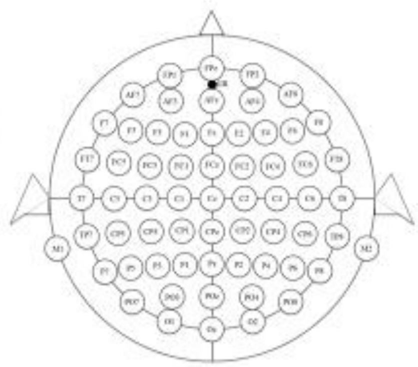
Interpreting Topography Maps





<u>Based on the Topography Maps:</u>

What are the most important brain areas when comparing awake vs. REM sleep?

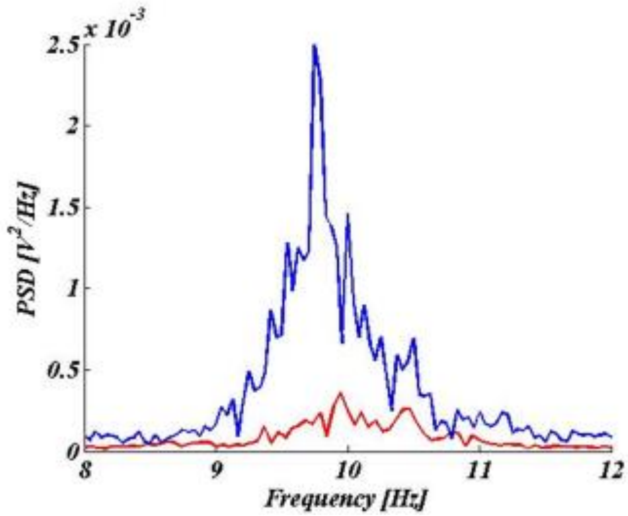


Source: Baird et al. eNeuro, 5 (4), 2018.

Activity: Guess that Behavior!

- **Channel: O1**

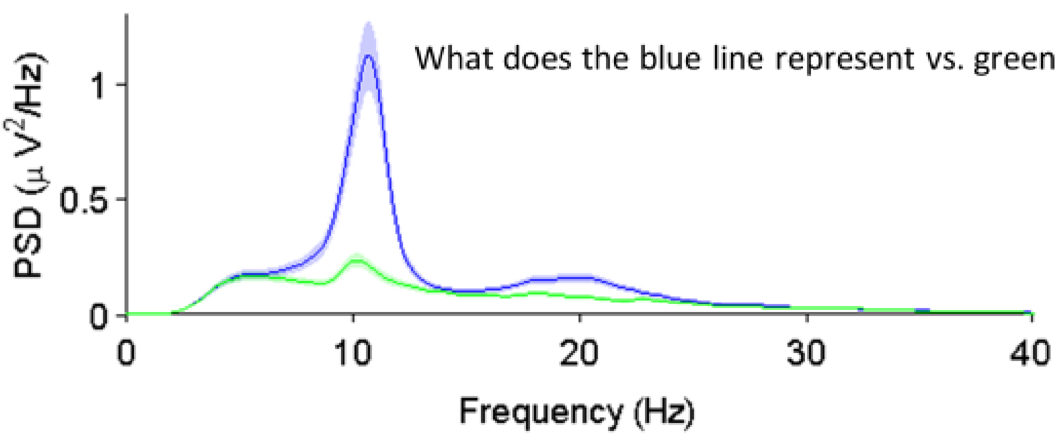
- What does the red line represent vs. blue line?



Activity: Guess that Behavior!

- **Channel: C4**

What does the blue line represent vs. green line?



Activity: Guess that Behavior!

- **<u>Channel: Cz</u>**

What does the blue line represent vs. green line?