Implementations and Applications of Brain-Computer Interfaces

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What is a Brain-Computer Interface?

- System that translates measurable brain activity into computer input
- Hardware component, can be invasive or non-invasive
- Software package to discern meaning from brain signals

Why are BCIs Important?

- Medical applications
- Enhancing existing computer tasks
- New capabilities for entertainment and connectivity

Outline

- Hardware
- Classification Algorithms
- BCI Input Paradigms
- Applications
- Conclusions

Electroencephalogram (EEG)

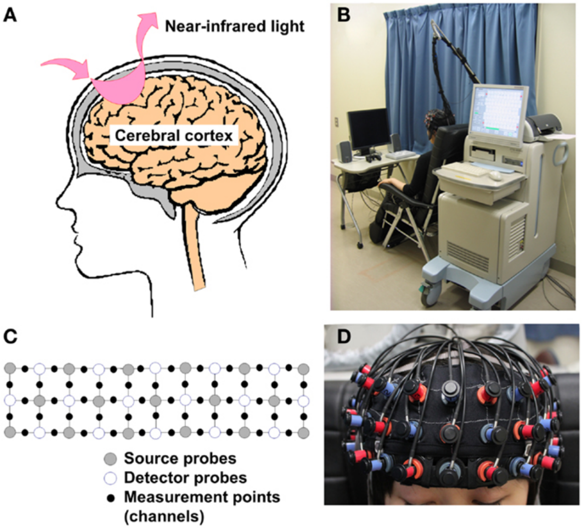
- Most common BCI hardware
- Measures electrical signals on scalp using electrode array
- High temporal resolution
- Historically used in epilepsy research and treatment

Electroencephalography (EEG)

Functional Near-Infrared Spectroscopy (fNIRS)

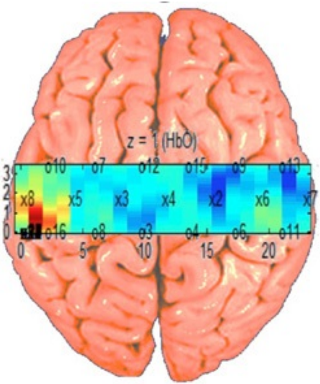
- Emits near-infrared light into the scalp
- Measures the light scattering due to red blood cell density and concentrations
- These measurements are correlated with brain activity
- Lower noise than EEG makes it ideal for passive input

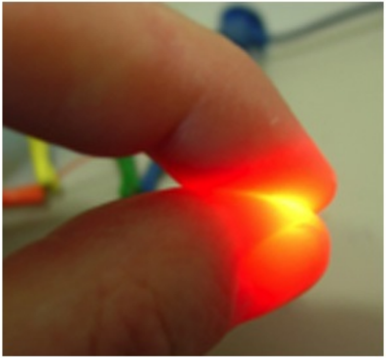
Functional Near-Infrared Spectroscopy (fNIRS)



Functional Near-Infrared Spectroscopy (fNIRS)

- Example: clenching the hand produces a fNIRS reading
- Near-infrared light passes easily through tissue





Signal Classifiers

- Responsible for converting data from hardware to data usable by software applications
- Each incoming signal is converted into a feature vector and then given a class
- Classes typically represent unique input types

Classifier Training

- Given pre-classified feature vectors, the classifier must learn to classify any vector
- Training set must be small and general enough to avoid overtraining
- Some machine-learning classifiers can perform online training, grouping similar vectors

Linear Classifiers

- Build linear boundaries between classes in an input space
- Boundaries referred to as hyperplanes, can divide an n-dimensional space into two subspaces
- Computationally cheap and reliable for BCI applications

Linear Discriminant Analysis

- Builds hyperplanes by maximizing the distance between the target class and the rest of the classes

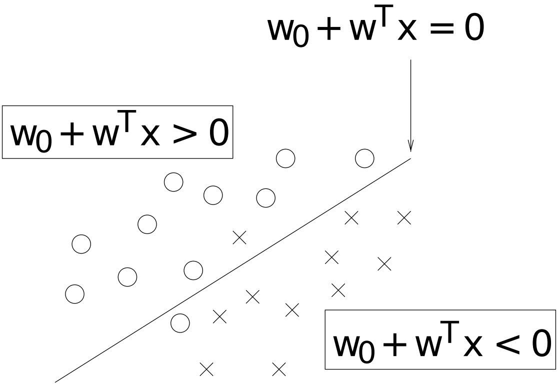
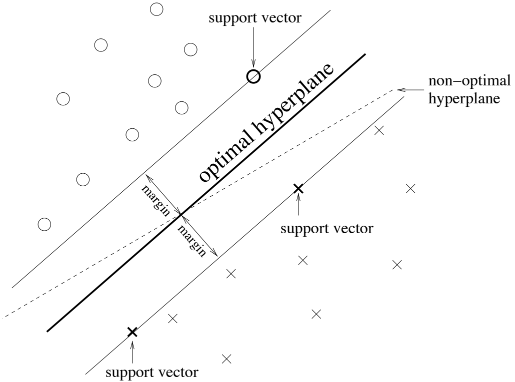


Figure: x is the input vector, w is the weight vector and w_0 is the threshold.

Support Vector Machines

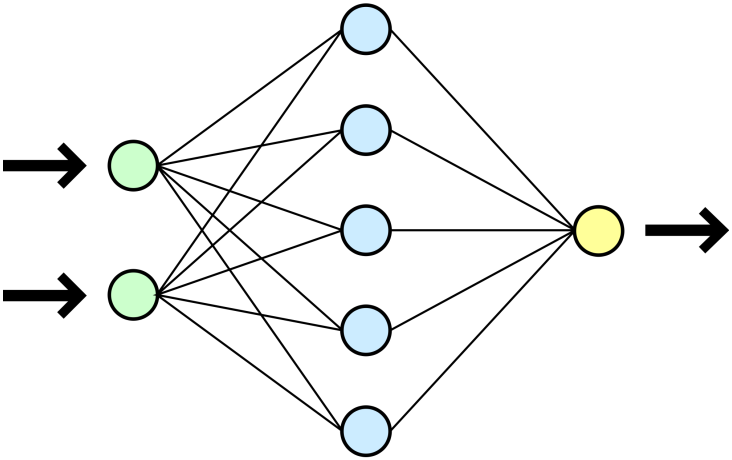
- Hyperplane is positioned to maximize the margins between it and the closest points of training data on either side



Support Vector Machines

- Generalize well to real-world data
- Resistant to overtraining and performance loss from increased dimensionality of feature vectors
  - "Curse of Dimensionality"

Neural Networks



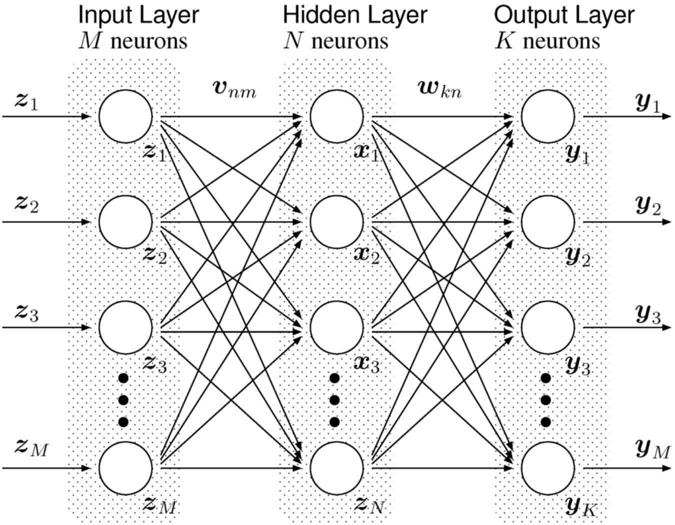
Neural Networks

- A collection of simulated neurons
- Have an input layer, output layer, and some number of hidden layers
- Inputs of each layer connected to the outputs of the previous layer
- Capable of classifying any number of individual classes
- Adaptive, can modify classification criteria during use

MultiLayer Perceptron

- Most commonly used neural network in BCI classification
- Very versatile and have been applied to most common BCI problems

MultiLayer Perceptron Diagram



MultiLayer Perceptron Operation

- Neurons contain activation functions built to mimic the action potentials of human neurons
- Training is performed by backpropagation, which changes connection weights based on amount of error in output vs. expected value
- Adaptive nature makes them more sensitive to overtraining

Improving Classification

- Gather more data
- Context sensitivity
  - Example: predictive typing / autocorrect
- Combining classifiers
  - Multiple classifiers in series (boosting)
  - Classifiers in parallel, majority decides final output (voting)
  - Parallel classifiers feeding one “meta-classifier” (stacking)

BCI Input Paradigms

- Active input
  - BCI data used as primary control mechanism
  - Often EEG based systems
- Passive input
  - BCI data used as auxiliary input
  - Applications: monitoring user stress, multimodal input with BCI and standard input devices
  - Interfaces using fNIRS input have become popular for these applications due to low interference from device operation

Medical Applications

- Among the first uses for BCIs
- Enable communication for people with severe motor disabilities
- Direct control of devices, robots, and prosthetics
- Brain state monitoring

Entertainment Applications

Entertainment Applications

- BCIs as game controllers
- Games are commonly used as tools in BCI research
- Commercial BCI games have already been released
- Remote control of home entertainment systems via BCI

User Interfaces

- Need a user-friendly way to use a BCI for general computer tasks
- McCullagh et al. have created a menu system and network structure to address this
- Capable of taking single commands or a stream of classified commands based on the context
- Communicates to networked devices via UPnP and other network protocols

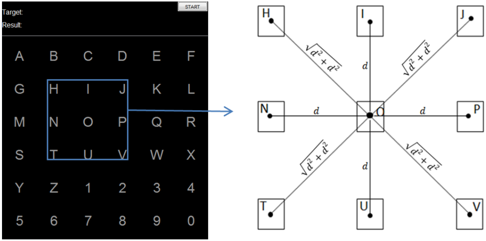
Spellers

- Spellers are keyboards for BCIs
- P300 speller has been popular in BCI systems
  - On a 6x6 grid, random rows and columns of symbols flash
  - User focuses on letter, counts the number of times it is highlighted
  - Problems: user fatigue and the close proximity of letters hinder accuracy
  - Example: External Video

The Zigzag Paradigm

- A modified P300 speller from Obeidat et al.
- Every other row is shifted right by $\frac{1}{2}$ of a character, maximizing distances between characters
- Improved accuracy from 80.6% to 91%
- Reduced user fatigue

Zigzag Paradigm Diagram



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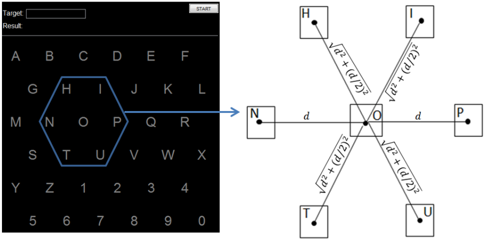

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Emerging Applications

- Control of vehicles
  - Poli et al. researched cooperative space navigation
  - DARPA has created a flight simulator controllable with a BCI
- Control of robots and UAVs
- Control of smart home “internet of things” devices

Conclusions

- Brain-computer interfaces can be very useful to people with disabilities
- Future work will allow a user to wirelessly control many devices in the home and access computing resources
- The entertainment applications utilizing a BCI have gotten closer to entering the mainstream
- Further improvements in hardware and classification will enable new applications as well as improving those in use

Questions?

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