Characterization of key properties of electroencephalographic signal for noninvasive brain machine/computer interface applications

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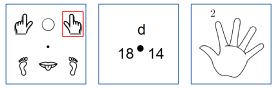
INTRODUCTION: We present an implementation of an electroencephalographic brain-computer interface (EEG BCI) based on mental motor imagery with up to 6 control states. We describe the results of the applications of this BCI with different subjects in offline as well as online interaction settings. We characterize various properties of EEG signal of relevance to EEG BCI applications. We describe the spatial and the temporal properties of the EEG signals in EEG BCI, the auto- and the cross-correlation properties, the BCI information content across EEG frequencies and electrodes, and the behavior of the EEG BCI with respect to the sample size and the electrode count. We derive recommendations for the time and voltage resolution as well as the dynamic range of the EEG data acquisition subsystems of the EEG BCI systems.

3/6-state motor imagery EEG BCI

EEG acquisition system → Synchronous trial extraction → Calculation of features → Selection of features → Machine learning classification → BCI Response

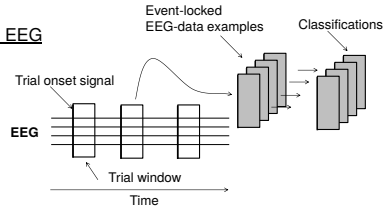
Nihon Kohden EEG-1200 medical EEG system with max 38 channels, 1000 Hz data acquisition rate, and 0.01 V voltage resolution

Offline User Interfaces:



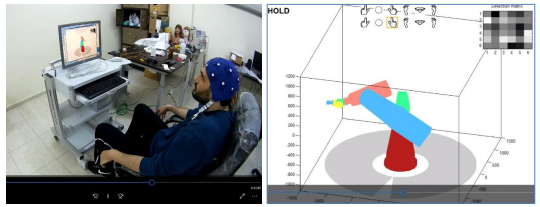
Machine learning algorithms
{ SVM, LDA, QDA, naïve Bayes, kNN, Random Forests, Neural Networks }

Synchronous EEG BCI model



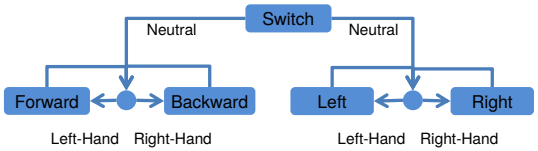
Subject	Total experiments	Subject's performance 2-State	Subject's performance 3-State	Subjects performance 6-State
BA	3	84%	60%	30%
EM	4	96%	82%	67%
ER	7	95%	85%	70%
HY	15	97%	91%	77%
ME	3	89%	59%	40%
MK	12	88%	67%	47%
MC	1	90%	74%	NA
SE	11	95%	79%	55%
YM	12	92%	73%	50%
ALL	**68**	**91%**	**74%**	**55%**

Online control of simulated robotic manipulator

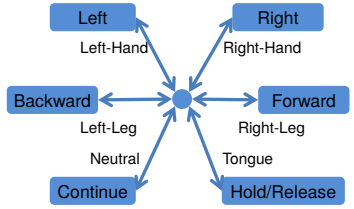


Control protocol for the robotic arm simulator

3-State protocol



6-State protocol

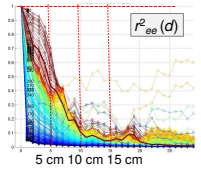


Our online experiments are currently ongoing; in the preliminary results we have:

3-State protocol - 80-85% control accuracy

6-State protocol - 50-55% control accuracy

Spatial properties of the EEG BCI signals

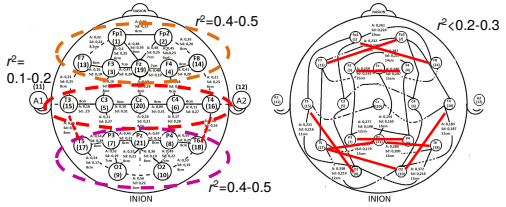


EEG electrodes at distances below approximately 5-8 cm are observed to exhibit strong correlations, approaching 1.0 for spatial separations less than 2-3 cm.

Only at distances greater than about 10 cm the EEG electrodes become fully uncorrelated.

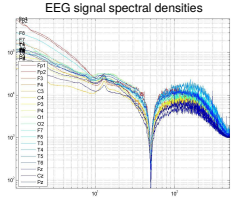
Next neighbor correlations

2-neighbor correlations



Temporal properties of the EEG BCI signal

EEG signal spectral densities

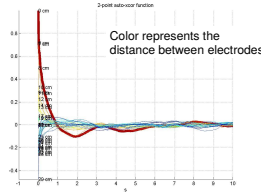


EEG spectra show similar structure over all electrodes, with power-law decay at small frequencies less than about 10 Hz and a local power spike around alpha-frequencies (not always seen).

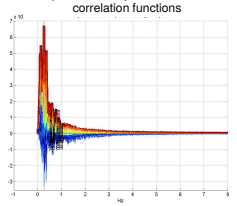
At high frequencies greater than 100 Hz a constant power-component is observed reminiscent of/possibly white noise.

The EEG channels show significant autocorrelations on scales of 0.1 sec. The EEG signal across different channels is correlated at much smaller time-scales less than 0.1 sec. This suggests that very high temporal resolution may not have a significant impact on the analysis of EEG signals.

EEG auto and X-correlation functions

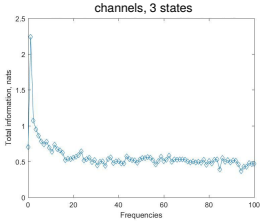


Spectral density of auto and X-correlation functions

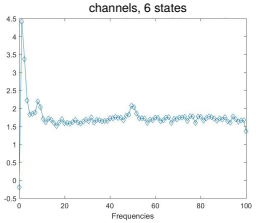


Information content of the EEG BCI signal

Naïve information per frequency, all channels, 3 states



Naïve information per frequency, all channels, 6 states

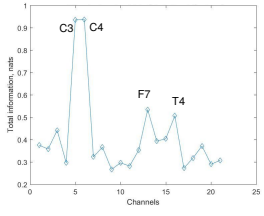


We quantify the mutual information between the EEG signal in BCI at different frequencies as well as at different electrode channels and the target BCI state.

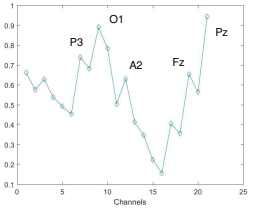
In frequency domain, majority of the information about the target BCI state is found to reside at low frequencies of less than about 10-15 Hz. This indicates that low-frequency EEG signals contain most of the useful information for BCI purposes.

The information available about the target BCI state is seen to vary strongly with EEG electrode channels. Such variation is both person- and task-specific. However, in all cases a smaller number of channels is seen to be the most informative about the BCI state. Mutual Information measure can be used to identify such channels.

Naïve information per channel, <=5Hz, 3 states

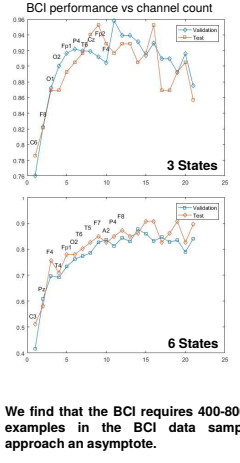


Naïve information per channel, <=5Hz, 6 states



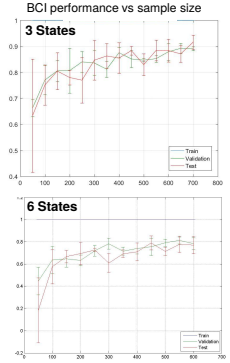
Sample size and electrode count behavior

BCI performance vs channel count



We find via direct inspection that significant proportion of the BCI performance can be recovered with relatively few EEG electrodes, which however are person- and task-specific.

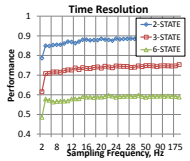
BCI performance vs sample size



We find that the BCI requires 400-800 task examples in the BCI data sample to approach an asymptote.

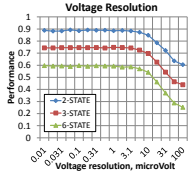
Time, voltage resolution of EEG data and dynamic range

Time Resolution



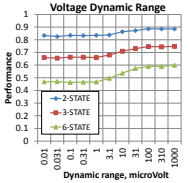
Increase in time resolution only affects the performance of BCI up to approximately 15-20 Hz, in all cases. The strongest increase is seen only for frequencies below 5-8 Hz.

Voltage Resolution



Increase in EEG voltage resolution only affects the performance of BCI up to the resolution of approximately 1-3 uV. Further refinements of voltage resolution in EEG acquisition system confers no noticeable improvements to the BCI state classification accuracy.

Voltage Dynamic Range



Dynamic range of EEG acquisition system affects the performance of the BCI quite weakly and only up to the dynamic ranges of approximately 100 uV. The impact of the dynamic range on the performance of BCI is stronger for higher-S BCIs.

Summary

- A EEG BCI capable of discriminating 2 to 6 motor imagery mental control states is presented
- This BCI is intended to be used in the future for the control of an assistive robotic manipulator system
- The information-properties of the EEG signal in relation to BCI applications are presented
- Guidelines for better design of the EEG BCI systems are discussed

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