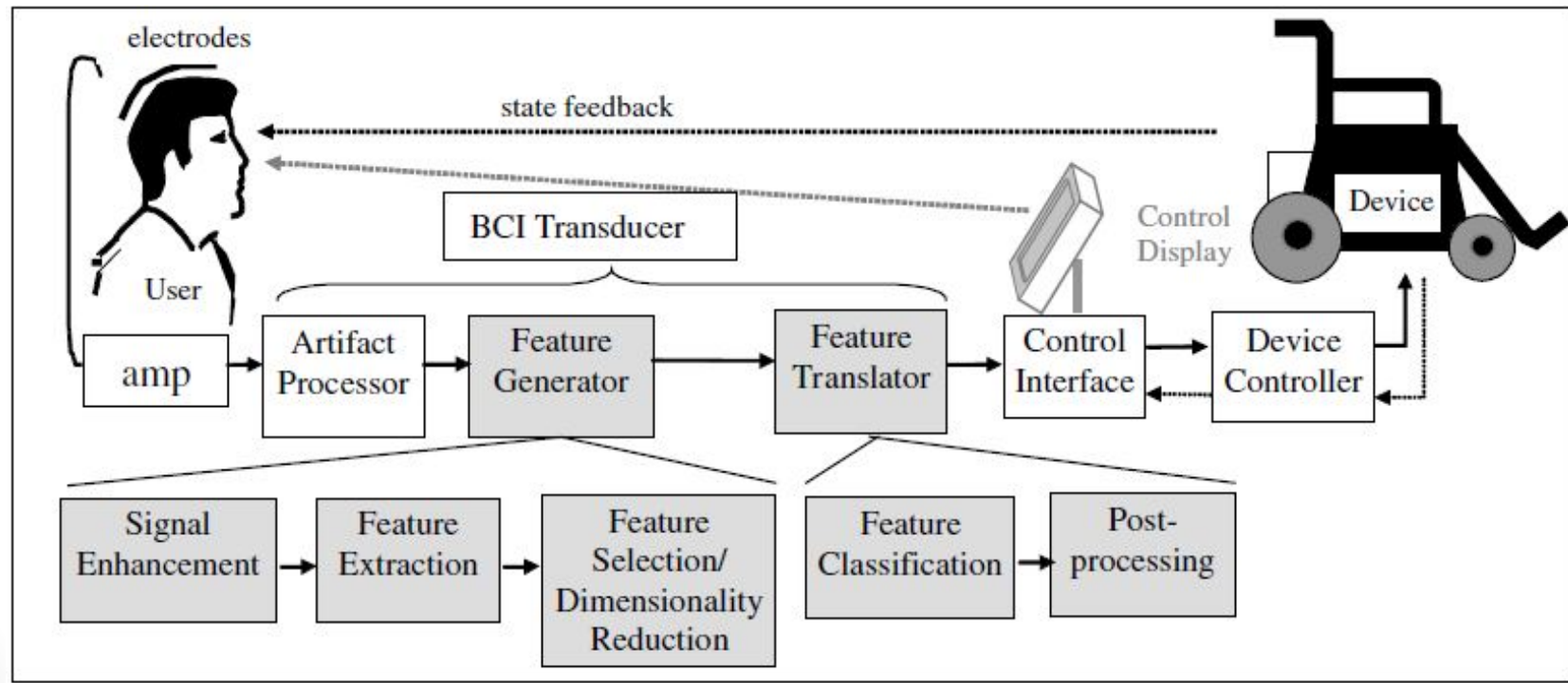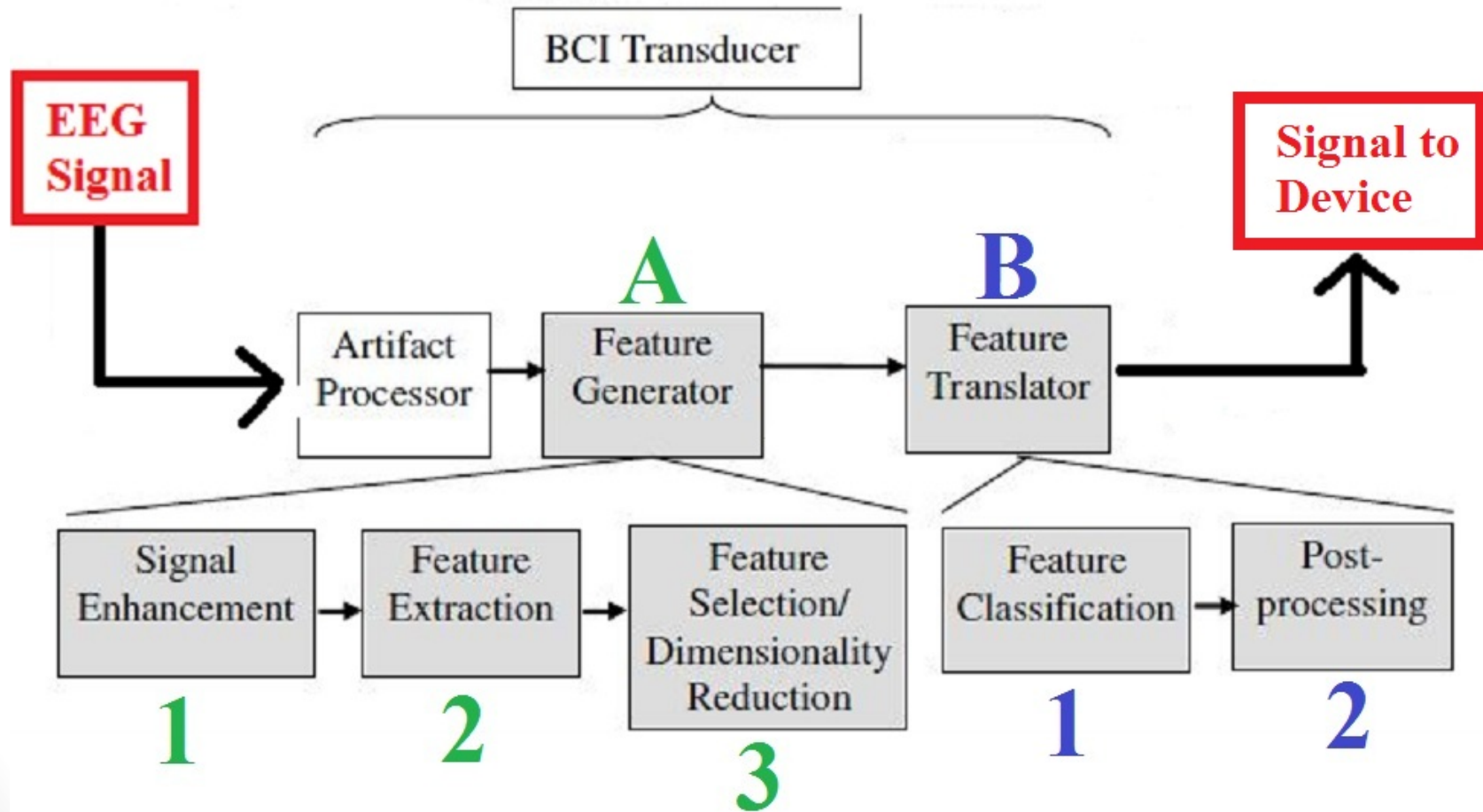# A survey of signal processing algorithms in BCIs based on electrical brain signals

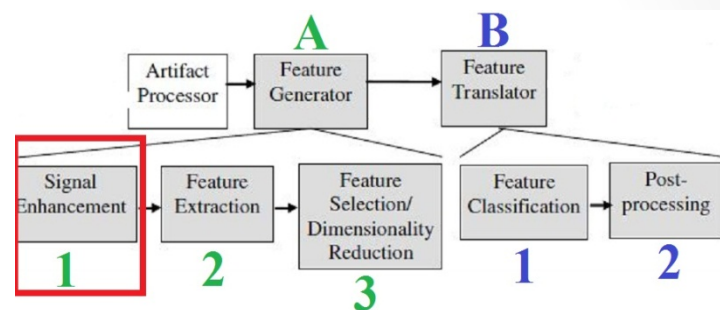Ali Bashashati et al

BCI Signal Flowchart

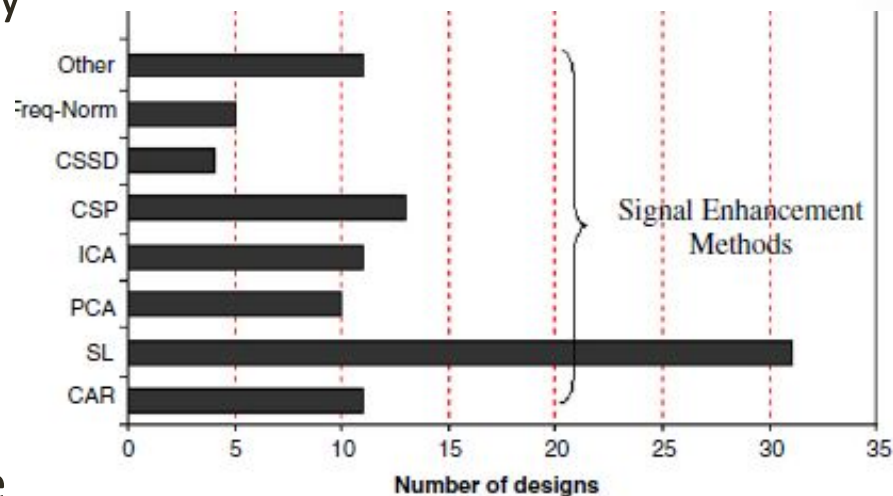# Essential Signal Processing Blocks

Signal Enhancement (A1)

- Purpose: Select or narrow in on certain channels to **increase Signal to Noise ratio**

- Referencing Methods
  - Choice of reference may vary across people/studies
- Examples
  - Large/Small Laplacian
  - Bipolar
  - Common Spatial Patterns
  - ICA/PCA
  - Common Average Reference

Feature Extraction (A2)

- Purpose: Derive quantitative representations of EEG data
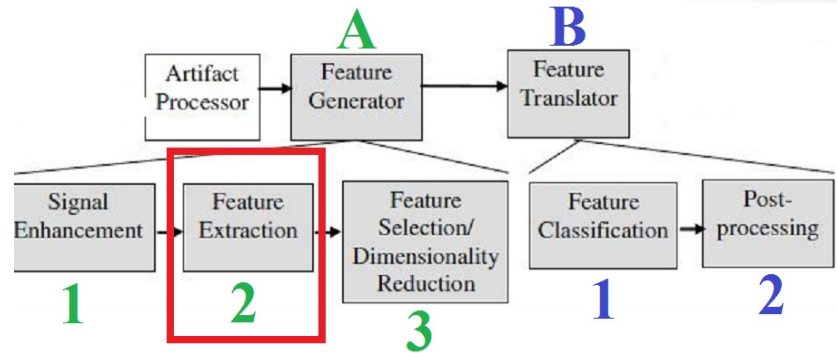
- Time/Frequency Examples
  - Power Spectral Density
  - Time-Frequency Representation
  - Correlative Time-Frequency Representation

- Parametric Modeling

Selection/Dimensionality Reduction (A3)

- Purpose: Reduce the dimensionality by selecting a subset of the features
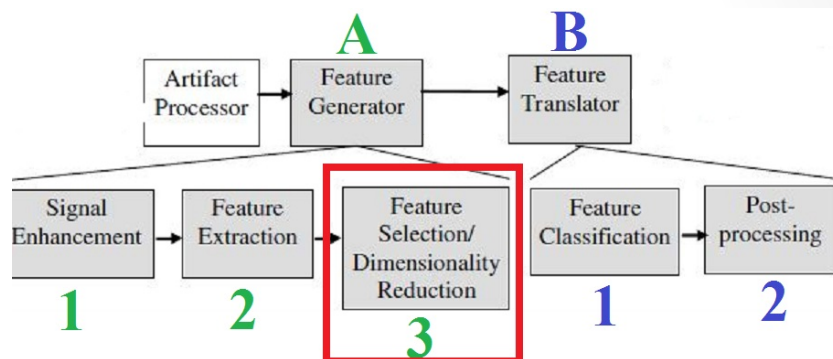
- Examples
  - Principle Component Analysis
  - Genetic Algorithms

Feature Classification (B1)

- Classifies the selected features to produce device controlling signals
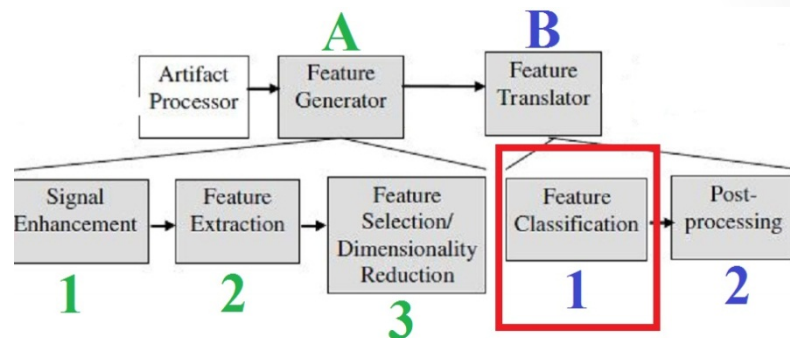
- Examples
  - Linear Classification

  - Non-Linear Classification
    - Kernal-based methods
    - Neural-networks

  - Classification Committee

Post-Processing (B2)

- Check for false activation of device
- Optional Block

- Examples
  - P300 Spell Check
  - Error potentials
  - Integration of positive signals
  - Refractory period/Debounce block

Flowchart Taxonomy

Table 1. Taxonomy for BCI transducer designs.

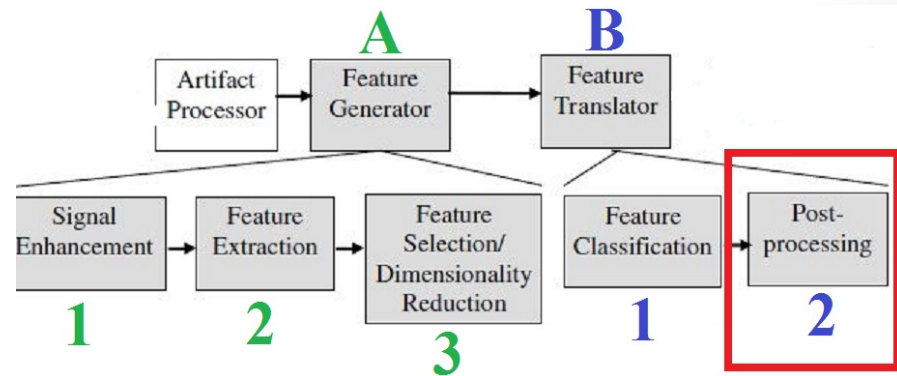| Item	Terms		Definition
BCI transducer	Artifact processor		Removes artifact from the input signal
	Feature generator	Signal enhancement	(1) Enhances signal-to-noise ratio of the brain signal
			(2) The output of this block is a signal with the same nature of the input (i.e. the output like the input is in the temporal domain).
		Feature extraction	Generates the feature vectors
		Feature selection/ dimensionality reduction	Selects a subset or reduces the dimensionality of features
	Feature translator	Feature classification	Classifies the features into logical control signals
		Post-processing	Increases the performance after feature classification, e.g., by blocking activations with low certainty

Acronyms

Index term	Description
AAR	Adaptive auto-regressive
AEP	Auditory evoked potential
AGR	Adaptive Gaussian representation
ALN	Adaptive logic network
ANC	Activity of neural cells
ANN	Artificial neural networks
AR	Auto-regressive
ARTMAP	Adaptive resonance theory MAP
ARX	Auto-regressive with exogenous input
BPF	Band-pass filter
C4.5	–
CAR	Common average referencing
CBR	Changes in brain rhythms
CCTM	Cross-correlation-based template matching
CER	Coarse-grained entropy rate
CHMM	Coupled hidden Markov model
CN2	–
CSP	Common spatial patterns
CSSD	Common spatial subspace decomposition
CSSP	Common spatio-spectral patterns
CTFR	Correlative time–frequency representation
CTFSR	Correlative time–frequency–space representation
DFT	Discrete Fourier transform
DSLVQ	Distinctive sensitive learning vector quantization
ERD	Event-related desynchronization
ERN	Event-related negativity

Index term	Description
ERS	Event-related synchronization
FLD	Fisher's linear discriminat
FFT	Fast Fourier transform
Freq-Norm	Frequency normalization
GA	Genetic algorithm
GAM	Generalized additive models
GLA	Generalized linear models
GPER	Gaussian process entropy rates
HMM	Hidden Markov model
ICA	Independent component analysis
IFFT	Inverse fast Fourier transform
k-NN	k-nearest neighbor
LDA	Linear discriminant analysis
LDS	Linear dynamical system
LGM	Linear Gaussian models implemented by Kalman filter
LMS	Least mean square
LPC	Linear predictive coding
LPF	Low-pass filter
LRP	Lateralized readiness potential
LVQ	Learning vector quantization
MD	Mahalanobis distance
MLP	Multi-layer perceptron neural networks
MN	Multiple neuromechanisms
MNF	Maximum noise fraction
MRA	Movement-related activity

Acronyms Continued

NID3	–
NMF	Non-negative matrix factorization
NN	Neural networks
OLS1	Orthogonal least square
OPM	Outlier processing method
PCA	Principal component analysis (a.k.a. Karhounen Loeve transform)
PLV	Phase locking values
PPM	Piecewise Prony method
PSD	Power-spectral density
RBF	Radial basis function
RFE	Recursive feature/channel elimination
RNN	Recurrent neural network
SA-UK	Successive averaging and/or considering choice of unknown
SCP	Slow cortical potentials
SE	Spectral-entropy
SFFS	Sequential forward feature selection
SL	Surface Laplacian
SOFNN	Self-organizing feature neural network
SOM	Self-organizing map
SSEP	Somatosensory evoked potential
SSP	Signal space projection
SSVEP	Steady state visual evoked potential
STD	Standard deviation
SVD	Singular value decomposition
SVM	Support vector machine
SVR	Support vector machine regression
SWDA	Stepwise discriminant analysis
TBNN	Tree-based neural network
TFR	Time–frequency representation
VEFD	Variable epoch frequency decomposition
VEP	Visual evoked potential
WE	Wavelet entropy
WK	Wiener–Khinchine
ZDA	Z-scale-based discriminant analysis