Dive into Neural Link & BCI Domain

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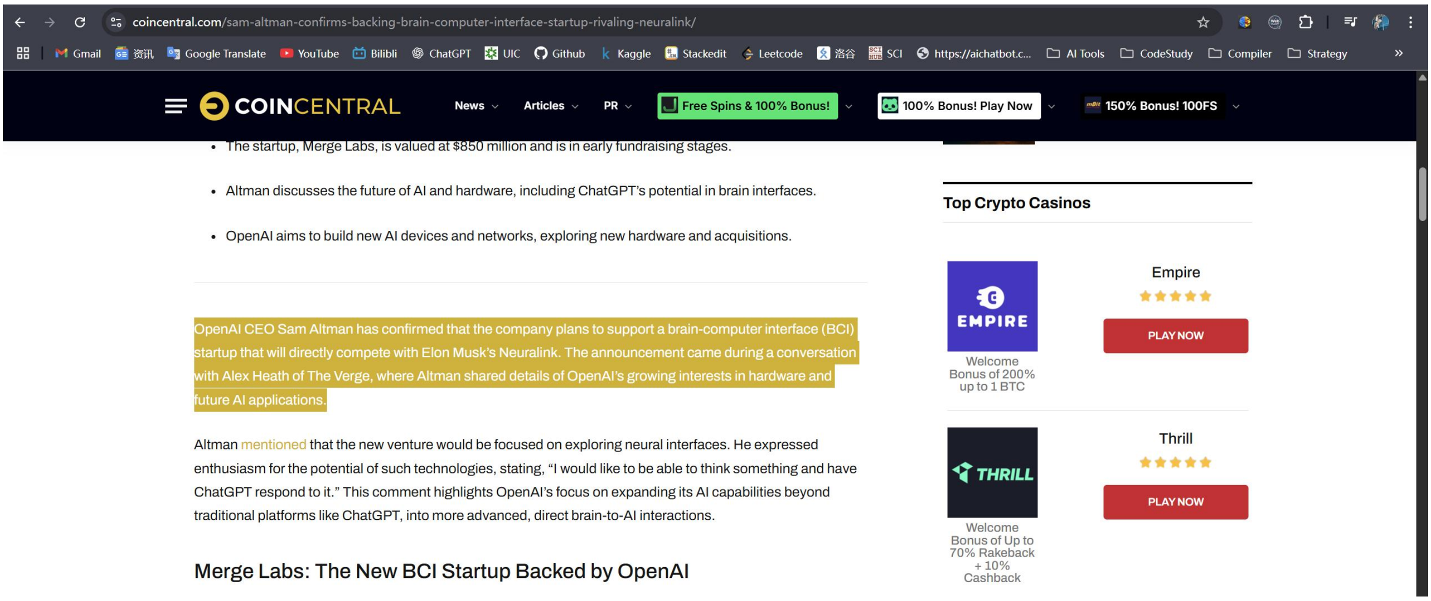
Neural link：脑机接口（Brain-Computer Interface, BCI） 技术，研发的一种超高带宽、可植入式脑机接口装置，使人类能够直接通过大脑与计算机进行交互（脑机接口的 target).

BCI Background News (~2025/8/16)



– ChatGPT's potential in brain interfaces: OpenAI CEO Sam Altman has confirmed that the company plans to support a brain-computer interface (BCI) startup that will directly compete with Elon Musk's Neuralink

– Neuralink 目前正在对重度瘫痪患者进行试验。该公司的目标是让患者能够用意念控制设备。今年 6 月，该公司完成了 6 亿美元的 E 轮融资，估值达到 90 亿美元。

– 据英国《金融时报》报道，萨姆·奥特曼正在与他人共同创立一家名为 Merge Labs 的脑机接口初创公司，并正在为其筹集资金，资金可能主要来自 OpenAI 的风险投资团队。这 家初创公司的估值预计为 8.5 亿美元

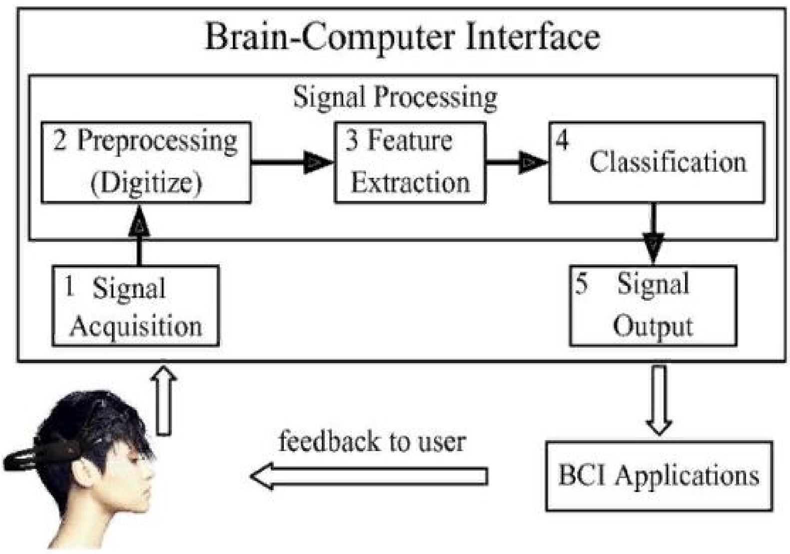
BCI Working Principle

植入电极：Neuralink 研发了一种柔性电极丝，比人类头发还细，可以通过手术植入到大脑皮层。这些电极能够记录神经元的电信号（input)，甚至可以进行电刺激。 （input & output）

信号采集与解码：电极捕捉到的神经信号（input）会传输到植入芯片。芯片通过算法将神经元的放电模式翻译成可识别的信息，例如控制电脑光标、机械手臂或输入文字（output）。

人机交互：最终实现人类“用意念控制”电子设备。

PS0: Overview of Some BCI System Structure & How dose it work?



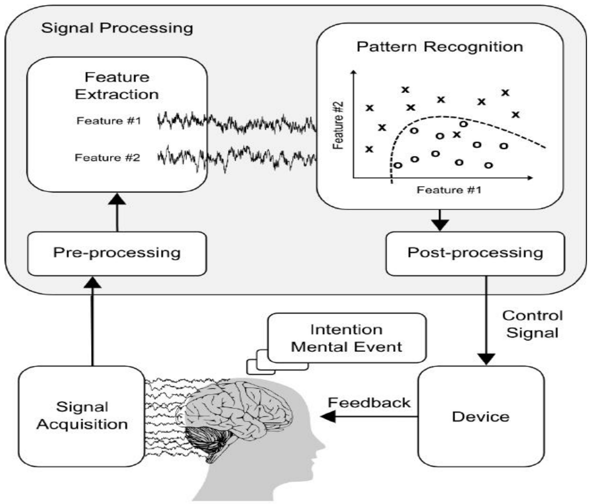
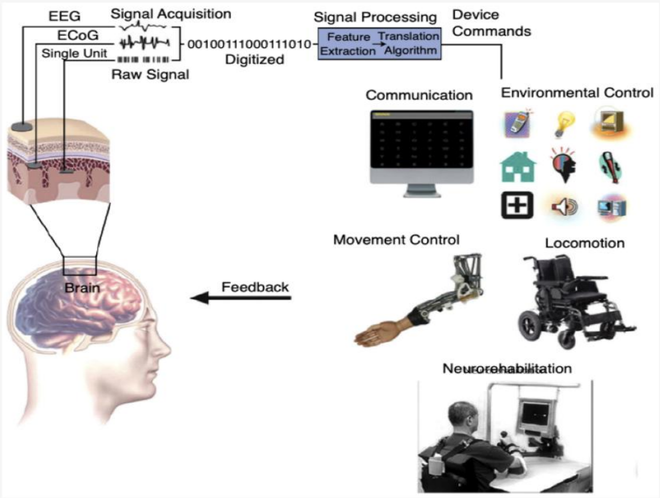
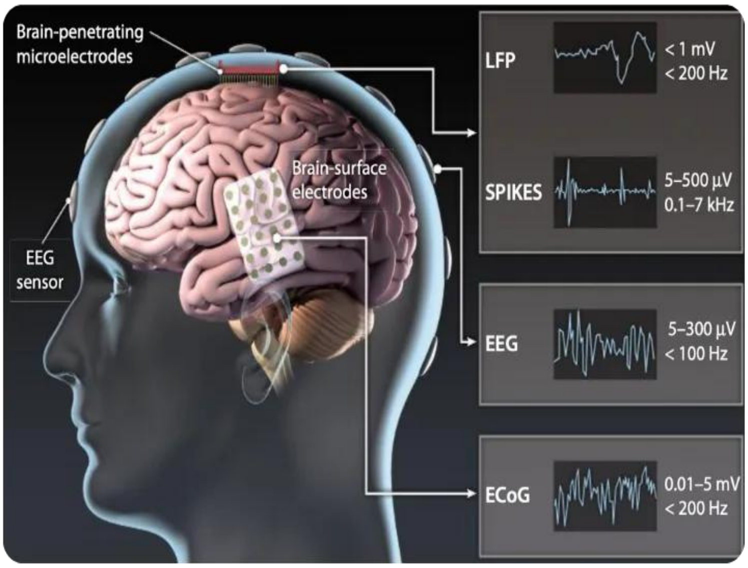


Figure 1. Components of a typical BCI system and its communication methods—simplified scheme.





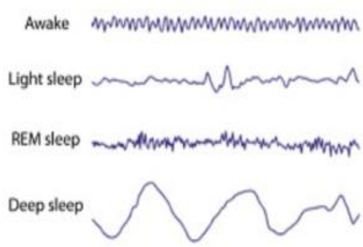
BCI System Component

1: Info Recordings (Ways of Recording NN Signal info: Raw Input)

To understand the brain's electrical activity at these scales, no single technology is enough. As a result, neuroscientists have a suite of tools at their disposal. Some of these, such as fMRI (功能磁共振成像： most widely known technology for recording neural activity) and EEG (脑电图), can be used in humans because they are non-invasive (非侵入性) ; they work through by looking into the skull.

Functional Magnetic Resonance Imaging (fMRI)

Figure 2. Magnetic Resonance Imaging. Left, a structural MRI, which shows the structure of the brain but does not reveal brain activity. Middle, a functional MRI (fMRI) scan (red areas) overlaid on a structural MRI image. The red regions were more active than other areas during the behavioural task. Right, diffusion tensor MRI (dtMRI) image, which reflects the ease with which water diffuses in the brain. The lines represent major neural pathways (but not the neuronal structures themselves), with different colours depicting different dominant directions (x, y, z) of the pathways. Note that only the middle panel, fMRI, gives any indication of brain activity.



1.1 fMRI (常见的电生理信号类型 fMRI + EEG + ECoG) & 1.2 EEG

脑电图（EEG）通过放置在受试者头皮上的电极直接记录大脑的电活动

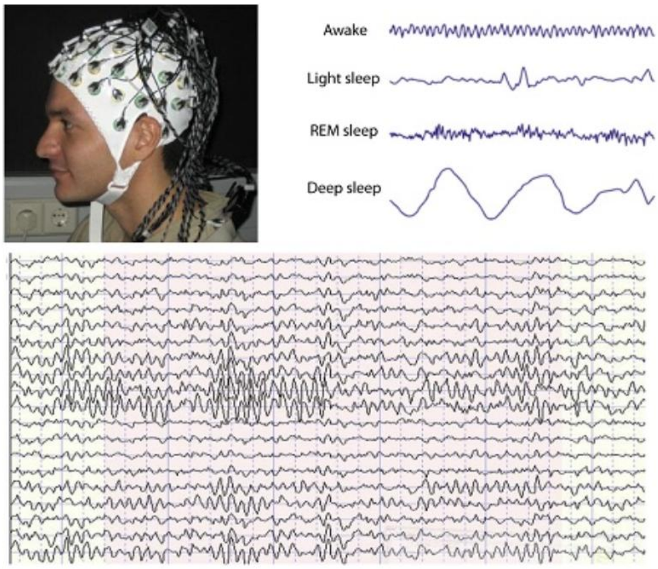
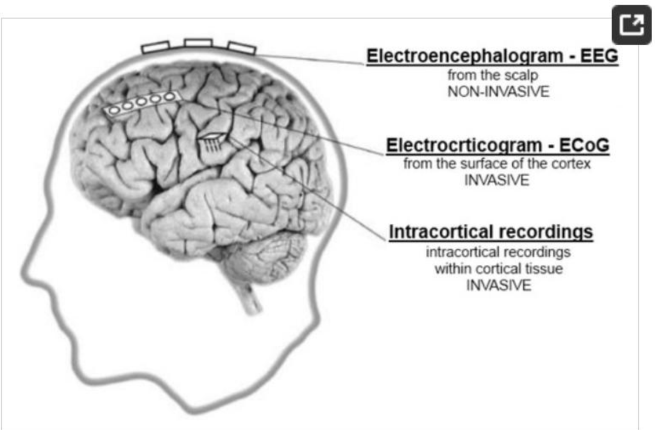
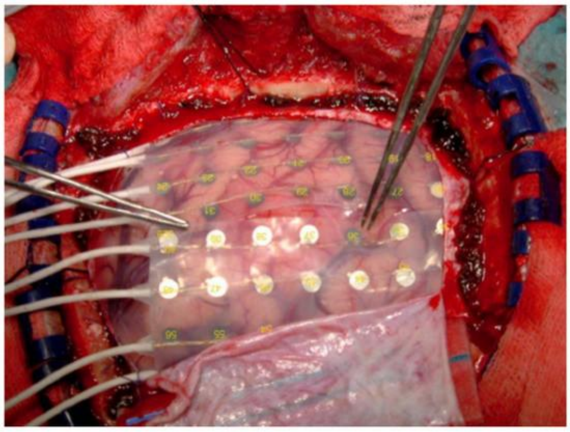


Figure 3. *EEG Recordings.* Top Left, *an EEG cap placed over a patient's scalp.* Top Right, *Example EEG Traces (4 seconds total) showing that different brain states correlate with different EEG waveforms.* Bottom, *Sample EEG recording. Recordings from individual electrodes are shown in separate rows. Vertical lines mark 1 second intervals.*

图 2 展示了三种用于记录大脑电活动的不同方法，包括一种非侵入性方法（EEG）和两种侵入性方法（ECoG 和皮层内记录）[3,27,31]





2: Info Recordings Digitized & Preprocessing (Preprocessing Stage)

从大脑神经信号到数字化信息的转换. 涉及神经信号的采集、处理、解码，并将其转化为计算机理解的数字信号.

2.1 信号放大与处理

放大信号：神经信号通常非常微弱，需要放大才能进行后续分析。放大器帮助增强这些微小信号。

去噪处理：大脑信号中会有很多噪声（如肌肉信号、外部干扰等），需要滤波和信号处理算法去除无用的噪声。

时域和频域分析：通过对信号进行时域和频域分析，提取出有用的特征。常用的方法包括：

小波变换（Wavelet Transform）

傅里叶变换（Fourier Transform）

自适应滤波（Adaptive Filtering）

2.2 信号解码 (https://www.scirp.org/journal/paperinformation?paperid=77330)

特征提取：通过处理后的信号，提取出代表大脑活动的特征（如信号的幅度、频率、相位等）。这些特征与具体的思维、运动等活动有对应关系。

模式识别 (feature & corresponding resp)：使用机器学习算法（如支持向量机 SVM、卷积神经网络 CNN 等）对特征进行分类和解码，将大脑的活动模式与具体的操作（如移动鼠标、控制假肢等）对应起来。

运动想象解码：通过解码大脑的运动意图，控制外部设备如机械臂或假肢。

视觉或听觉解码：通过解码大脑对视觉或听觉刺激的响应，帮助恢复感知功能

PS1: Overview of The Framework of Proposed Overall BCI System Pipeline

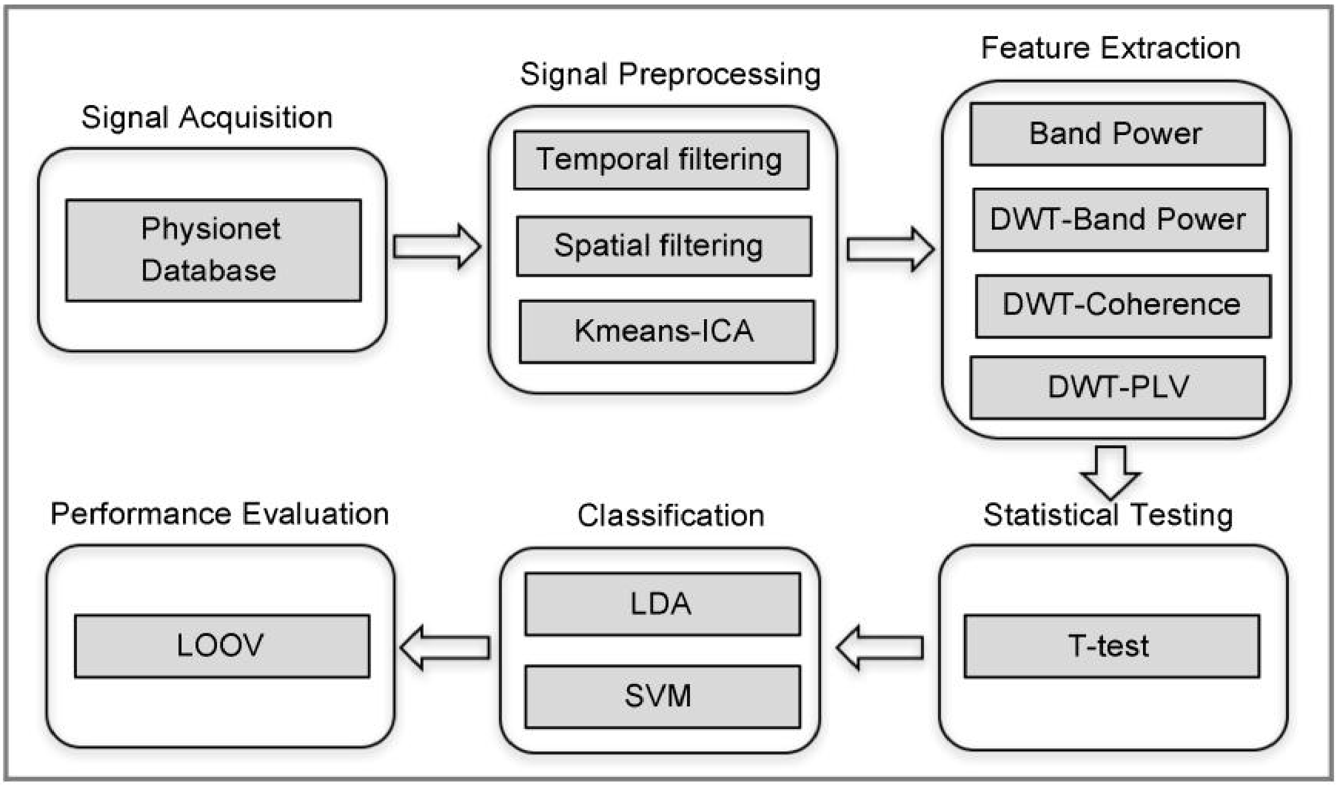
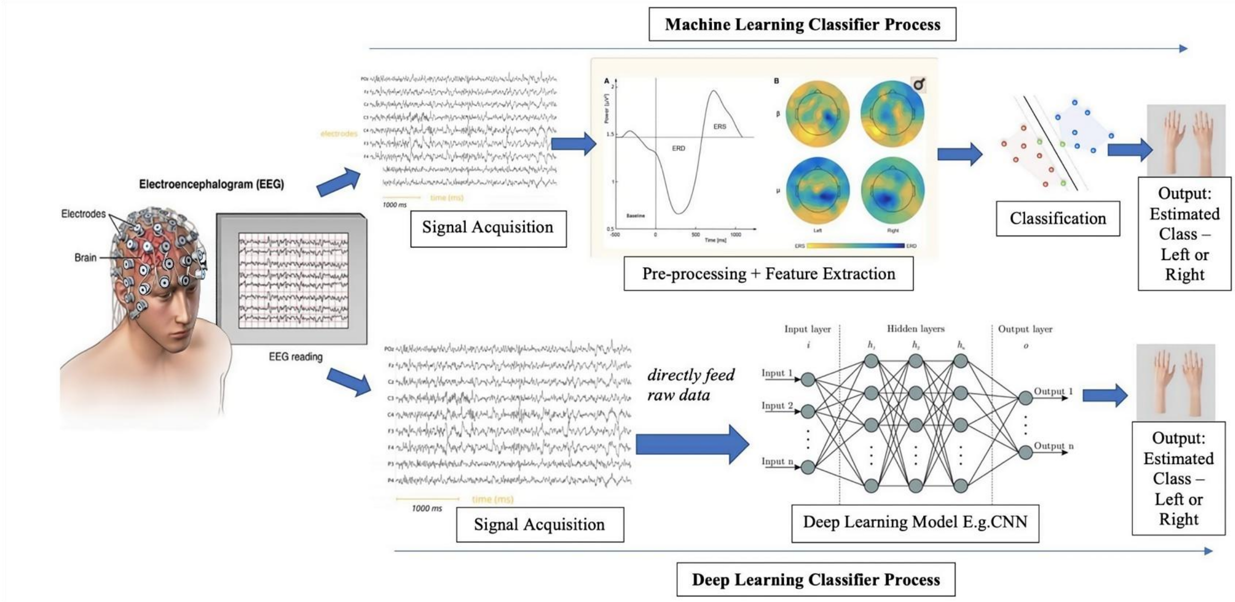
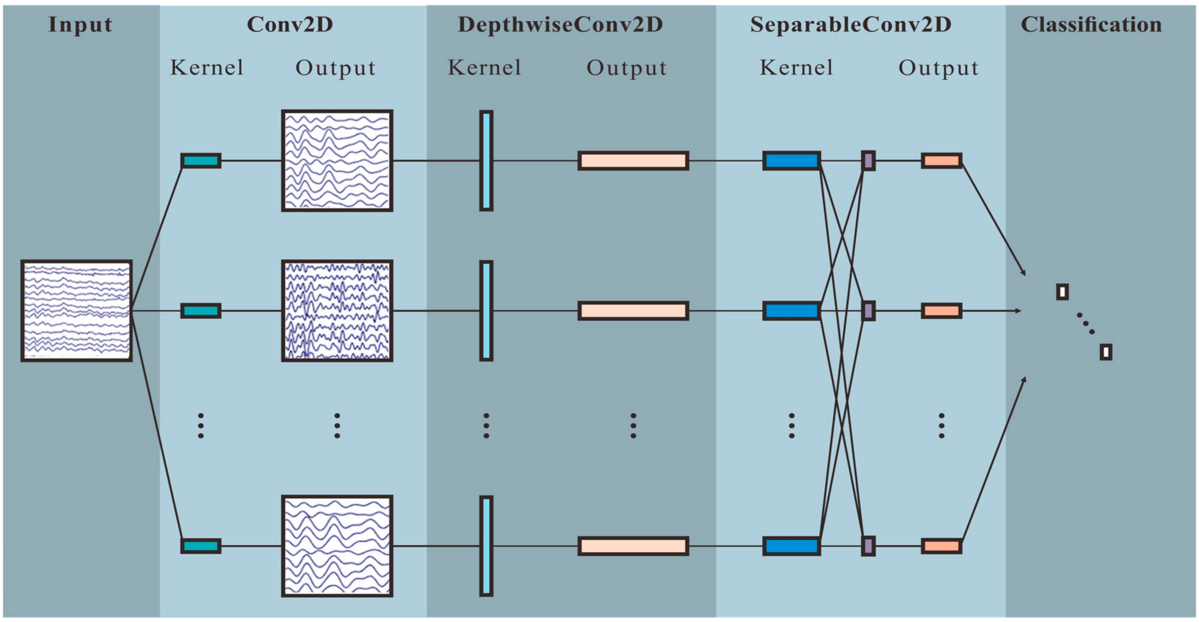


Figure 1. Framework of the proposed BCI system. Signal preprocessing and feature extraction are performed prior to statistical testing. Selected features are adopted for classification using a LDA and SVM based on a LOOV scheme. ICA: Independent Component Analysis; DWT: Discrete Wavelet Transorm; PLV: Phase Locking Value; T-test: Student test; LDA: Linear Discriminant Analysis; SVM: Support Vector Machine; LOOV: Leave One Out Corss Validation.

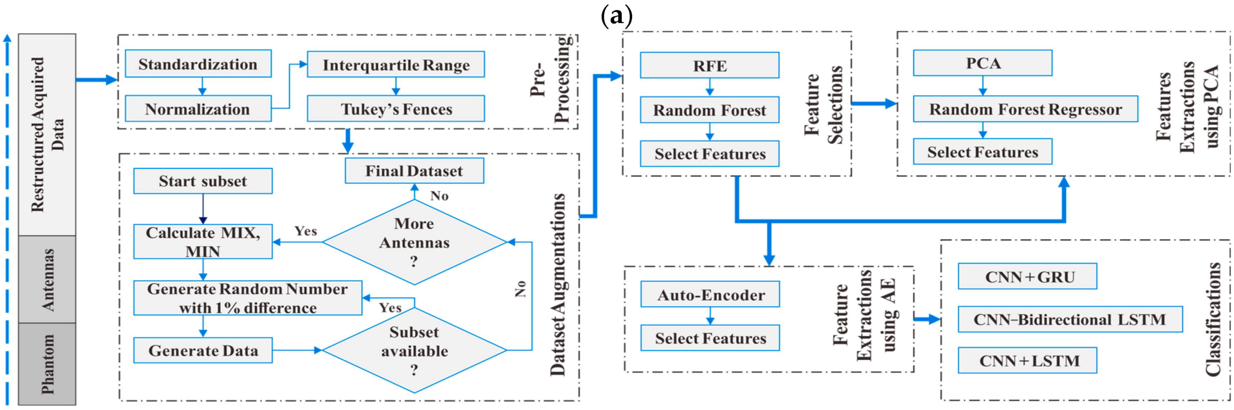
PS2: Visualization of The Framework of Proposed Overall BCI System Pipeline



PS3: Overview of The Framework of Feature Extraction (EEG→ EEGNet)



(a)



(b)

Figure **(a)** Sequential processing stages of EEGNet (adapted from [63]), showing temporal filtering (Conv2D), frequency-specific spatial filtering (DepthwiseConv2D), and feature map integration (SeparableConv2D), followed by classification. **(b)** An integrated deep learning pipeline for neural signal classification (adapted from [67]), demonstrating the sequential stages of data augmentation, feature selection, feature extraction, and classification.

3: Digital signal conversion and feedback

Input: The preprocessed data from Step2. Preprocessing (信号放大与处理 + 信号编码)

· **输出到计算机：**解码后的信号可以直接控制计算机、机器或外部设备。比如通过大脑信号控制光标移动，或者通过思想来操控机械臂。

· **实时反馈：**设备通常会提供实时反馈，确保用户能感知到操作结果。例如，运动控制时的触觉反馈、视觉反馈等

4: Bi-Direction Communication

信号输入：BCI 不仅仅是“输出”控制信号，还可以通过脑电刺激（如深脑刺激）将信号反馈到大脑中。这使得大脑和外部设备能够进行双向互动。**例如：**对失明患者提供视力反馈，或对运动障碍患者提供感觉刺激

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