# Chapter 2

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**The Electroencephalogram – A Brief Background**

- The human brain is the most complex organic structure, leading to extensive research from molecular to cognitive levels.
- Early electrical activity in the brain was first recorded by Richard Caton in 1875 on rabbits and dogs, showing microvolt-range signals on the cerebral cortex.
- Hans Berger later recorded time-varying, oscillating electrical "brain waves" from the human scalp, noting variations across different scalp locations.
- Berger observed that these waves varied depending on:
- Neurological health
- Mental states (e.g., attention, relaxation, sleep)
- Berger's work laid the foundation for **electroencephalography (EEG)**, a noninvasive clinical tool used to:
- Understand brain function
- Diagnose brain disorders
- EEG interpretation involves analyzing:
- Frequency
- Amplitude
- Morphology
- Spatial distribution of brain waves
- Despite progress, no comprehensive biological or mathematical model explains all EEG patterns; interpretation remains largely **phenomenological**.
- Historically, EEG was interpreted solely through **visual inspection**, but this is now supported by **digital signal processing (DSP)** methods.
- DSP enhances EEG analysis by:
- Improving signal-to-noise ratio (SNR)
- Quantifying signal features
- Extracting hidden information
- Signal processing for EEG falls into two main categories:

1. **Spontaneous activity analysis** (background EEG)
2. **Evoked potentials (EPs)** analysis – relies heavily on DSP due to the complexity and low amplitude of EP signals.

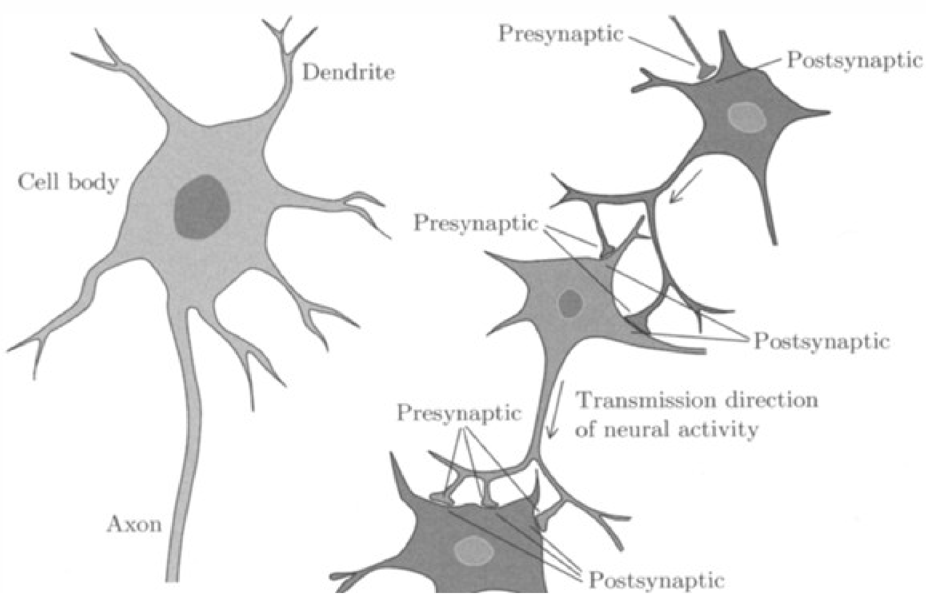
**Advancements in Brain Imaging and the Role of EEG**

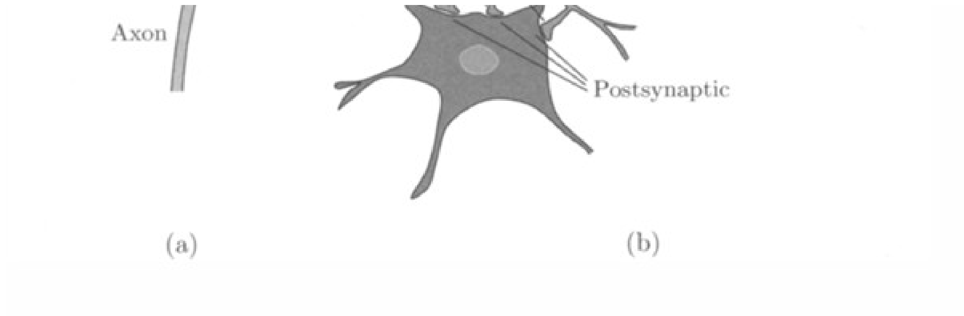
- Brain function research has advanced with imaging modalities such as:
- **Positron Emission Tomography (PET)**
- **Single Photon Emission Computed Tomography (SPECT)**
- **Magnetic Resonance Imaging (MRI)**
- These techniques provide **2D or 3D images** with good spatial resolution and offer additional insights on **anatomy** and **blood flow**, supplementing electrophysiological data.
- Despite reduced dominance in clinical use, **EEG remains vital** for diagnosing:
- Epilepsy
- Sleep disorders
- Dementia
- EEG is crucial for **real-time monitoring** in:
- Operating rooms
- Intensive care units
- Coma or encephalopathy patient tracking
- EEG's **temporal resolution (fractions of a second)** surpasses that of PET, SPECT, and MRI.

- EEG is also **cost-effective**:
- Requires basic equipment: electrodes, amplifier, PC
- Minimal technical demands compared to neuroimaging
- **Magnetoencephalogram (MEG)** is another noninvasive technique:
- Measures weak magnetic fields of neural activity using **SQUID** sensors
- Advantage: **Magnetic fields are less distorted** by the skull than electrical signals
- Initially thought to provide **independent information**, MEG is now known to be **strongly interdependent** with EEG signals.
- EEG, MEG, and imaging techniques each have **unique strengths and limitations** and should be **used complementarily**.
- Chapter Overview:
- **Section 2.1**: Overview of the nervous system and brain's electrical activity
- **Section 2.2**: Common EEG patterns and waveforms
- **Section 2.3**: Standard EEG recording techniques
- **Section 2.4**: Key EEG applications

**Structure and Function of the Nervous System**

- The **nervous system** is responsible for collecting, communicating, and processing information to respond to internal and external changes efficiently.
- It is divided into two main parts:
- **Central Nervous System (CNS)**: Brain and spinal cord
- **Peripheral Nervous System (PNS)**: Connects CNS to body organs and sensory systems
- The CNS and PNS work in coordination:
- **Afferent (sensory) nerves** carry signals to the CNS
- **Efferent (motor) nerves** carry responses from the CNS to the body
- A **functional division** of the nervous system includes:
- **Somatic Nervous System**: Controls voluntary muscle movement and relays physical sensations
- **Autonomic Nervous System**: Regulates involuntary activities (e.g., heart, bladder, uterus)
- The autonomic nervous system has two opposing subsystems:
- **Sympathetic Nervous System**: Active during physical activity or fear (increases heart rate)
- **Parasympathetic Nervous System**: Dominant during relaxation (decreases heart rate)
- Both subsystems **innervate the same organs** to maintain internal balance.
- **Heart rate variability** arises from this antagonistic interaction and is a key research area in understanding links between neurological diseases and autonomic dysfunction.
- Methods for quantifying heart rate variability are discussed in **Chapter 8**.





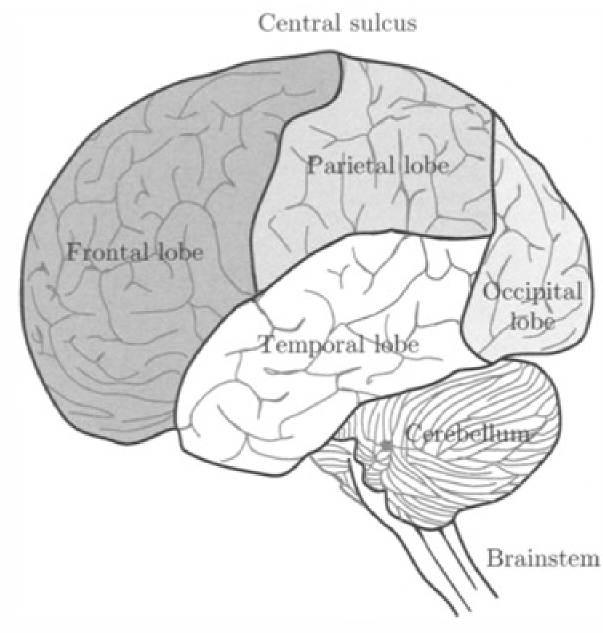

**The Neuron – Functional Unit of the Nervous System**

- The **neuron** is the basic functional unit of the nervous system, responsible for transmitting information to and from the brain.
- While neurons vary in **size, shape, and function**, they are collectively referred to as neurons.
- Based on **functionality**, neurons are categorized into three types:
- **Sensory neurons**: Connected to sensory receptors
- **Motor neurons**: Connected to muscles
- **Interneurons**: Connected to other neurons
- **Structure of a typical neuron** (Figure 2.1(a)):
- **Soma (cell body)**: Central part of the neuron
- **Dendrites**: Multiple branches (up to thousands) that receive signals from other neurons ($\leq$ 2 mm in length)
- **Axon**: Single, long branch that sends output signals (can be >1 m in length)
- **Synapse**: Junction where an axon's terminal contacts another neuron to transfer information.
- Signal transmission:
- Begins in the soma and travels as a **pulse-shaped electrical signal** (action potential) along the axon
- At the synapse, the **electrical signal is converted to a chemical signal** (neurotransmitter)
- The chemical diffuses across the **synaptic gap**, then reconverted to an electrical signal in the postsynaptic neuron (Figure 2.1(b))
- In the postsynaptic neuron:
- **Summation** of multiple synaptic inputs occurs
- Signal amplitude depends on **number** and **timing** of inputs
- If the summed signal **exceeds a threshold**, the neuron fires an action potential
- Not all inputs are excitatory—some are **inhibitory**, due to specific chemical structures that prevent neuron excitation.

**Neural Computation and Signal Transmission**

- A **postsynaptic neuron** receives both **excitatory and inhibitory** inputs; its output is determined by how these inputs are **summed together**.
- This summation and response mechanism is termed a **neural computation**, performed billions of times across neurons.
- Electrical activity within neurons differs from scalp measurements:
- Along the axon, signals appear as **action potentials**—uniform waveforms of **identical amplitude**
- This is due to the **"on/off" property** of neurons:
- An action potential either occurs at full amplitude or **not at all**
- **Signal intensity** is encoded by the **firing rate**, not waveform size
- Examples of rate-based signaling:
- **High firing rate in sensory neurons** = Strong pain sensation
- **High firing rate in motor neurons** = Strong muscle contraction
- This firing-rate modulation:
- Is ideal for **long-distance transmission**
- Is **robust** to local signal failures

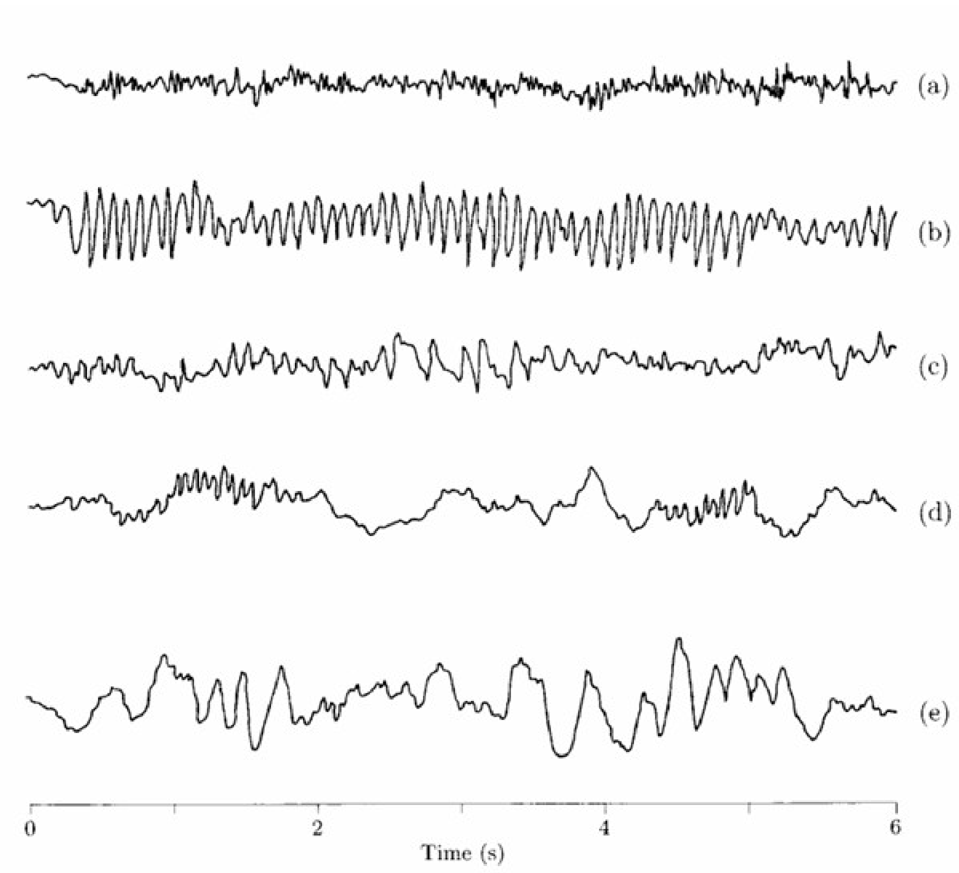
- Is limited by the **refractory period**, during which the neuron cannot fire again
- Neurons form **interconnected circuits (neural networks)** to process specific types of information.
- Example: **Knee-jerk reflex circuit**:
- Triggered by a hammer tap stimulating **muscle receptors**
- Signal travels via **afferent pathway** to the CNS
- Sensory input activates **motor neurons via synapses**
- Response signal travels back to muscle, causing **contraction** and visible **knee-jerk reaction**




**The Cerebral Cortex and Its Functional Regions**

- The **cerebral cortex** is the most critical part of the CNS, responsible for:
- Sensation
- Learning
- Voluntary movement
- Speech
- Perception
- It is the **outer layer of the cerebrum**, measuring **2–3 mm thick**, but due to its **highly folded surface** (ridges and valleys), it covers an area of about **2.5 m²** and contains **over 10 billion neurons**.
- The cortex is split into two **symmetrical hemispheres** (left and right), separated by the **sagittal fissure** (central sulcus).
- Each hemisphere is divided into **four lobes** (Figure 2.2):
- **Frontal lobe**
- **Temporal lobe**
- **Parietal lobe**
- **Occipital lobe**
- **Key functional areas**:
- **Motor cortex**: Located just anterior to the central sulcus in the frontal lobe; controls **voluntary movement**
- Large subareas are dedicated to tasks needing fine control (e.g., **speech**, **facial expressions**, **finger movements**)
- **Auditory cortex**: In the **superior temporal lobe**, processes **hearing**
- **Visual cortex**: At the **posterior occipital lobe**, processes **vision**
- **Somatic sensory cortex**: Just posterior to the central sulcus in the **parietal lobe**, processes **touch and body sensation**
- These are known as **primary cortical areas**, each with neurons **specialized** for specific functions.

- Surrounding these are **larger secondary areas**, essential for advanced mental processing:
- Analyze features like **shape**, **color**, **size**
- Provide **associative links** between senses
- **Integrate new information** with past experiences and knowledge




**EEG Rhythms and Cortical Electrical Activity**

- The combined electrical activity of the **cerebral cortex** is referred to as a **rhythm**, due to the **oscillatory and repetitive** nature of the signals.
- **Single-neuron activity** is **not measurable on the scalp** due to attenuation from tissues like **fluids, bone, and skin**.
- However, **collective activity of millions of neurons**, even several millimeters deep, generates a **measurable electrical field** at the scalp.
- These fields are primarily produced by **synaptic excitation of dendrites**, generating **excitatory postsynaptic potentials**.
- While **intracerebral recordings with microelectrodes** can measure few neurons directly, such methods are **invasive** and not discussed further in this text.
- **EEG rhythms vary widely** and are influenced by the subject's **mental state** (e.g., attention, wakefulness, sleep).
- **Figure 2.3** shows examples of EEG rhythms associated with different states.
- EEG rhythms are defined by:
- **Frequency range**
- **Relative amplitude**
- **Amplitude** of EEG signals depends on the **synchrony** of cortical neuron firing:
- **Synchronous excitation**: High amplitude, rhythmic, coherent waveforms
- **Asynchronous excitation**: Low amplitude, irregular waveforms
- *Note: The number of involved neurons may be the same in both cases.*
- **EEG frequency** is influenced by:

- **Thalamic input**: Thalamic neurons have **pacemaker properties**, firing rhythmically on their own
- **Cortical feedback**: Local cortical neuron interaction without pacemaker activity can also generate rhythms through **circuit feedback mechanisms**

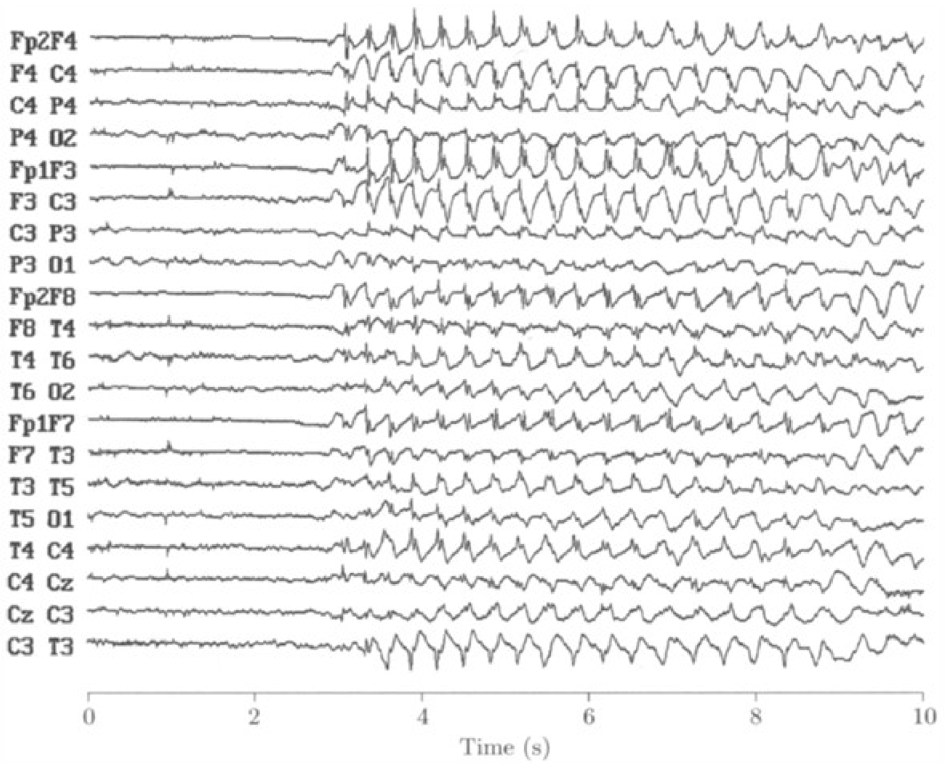
**Interpretation of EEG Rhythms and Brain States**

- **High-frequency / low-amplitude rhythms** indicate an **active brain** state, typically seen during:
- **Alertness**
- **Dream sleep (REM)**
- **Low-frequency / high-amplitude rhythms** are associated with:
- **Drowsiness**
- **Non-dreaming (deep) sleep**
- **Reasoning behind this relationship**:
- During active states, cortical neurons are **highly active** but **unsynchronized**
- Each neuron (or small group) processes different parts of complex tasks
- They **fire rapidly**, but **out of sync** with neighbors → results in **low synchrony** and thus **low EEG amplitude**
- During deep sleep, neurons are **not processing information**, but are **collectively excited** by rhythmic input
- This leads to **high synchrony** and **high EEG amplitude**
- Despite many **unexplained aspects of EEG rhythms**, and only **hypothetical explanations** so far, analyzing and **quantifying these rhythm characteristics** remains a **valuable clinical method** for assessing **brain functional states**.

### Common EEG Rhythms and Their Characteristics

- **EEG signals recorded from the scalp** typically have:
  - **Amplitudes**: From a few microvolts up to ~100 µV
  - **Frequency range**: 0.5 to 30–40 Hz
- These rhythms, also called **background rhythms**, are grouped into **five frequency bands**, though the classification is coarse and relative to **age** and **mental state**.
- **Newborns** show higher frequency content compared to **adults**.
- **EEG Frequency Bands** (as per [13]):
  - **Delta rhythm (< 4 Hz)**
    - Large amplitude
    - Common during **deep sleep**
    - Abnormal in **awake adults**, may indicate **cerebral damage or encephalopathy**
  - **Theta rhythm (4–7 Hz)**
    - Appears during **drowsiness** and **certain sleep stages**
  - **Alpha rhythm (8–13 Hz)**
    - Prominent in **relaxed, awake subjects with eyes closed**
    - **Suppressed** when eyes are open
    - Highest amplitude in **occipital regions**
  - **Beta rhythm (14–30 Hz)**
    - **Fast**, **low-amplitude** rhythm
    - Seen in **activated cortex** and **some sleep stages**
    - Observed mainly in **frontal and central scalp regions**
  - **Gamma rhythm (> 30 Hz)**
    - Linked to **active cortical information processing**
    - Can be detected during **finger movements** using sensitive recordings over the **sensorimotor area** [14]
- **Rhythm duration**:
  - Most rhythms can persist for **several minutes**
  - Some (e.g., **gamma rhythm**) may last only **a few seconds**

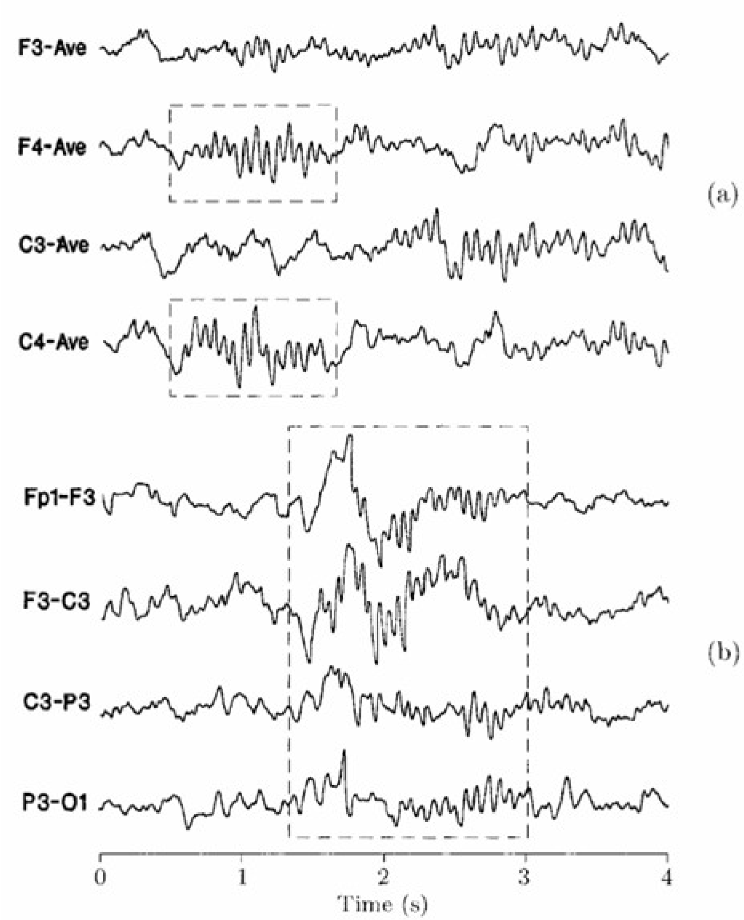
- It's important to note that:
  - A single rhythm is **not always continuously present**
  - Long periods of **irregular or arrhythmic** EEG signals are common




**Spikes, Sharp Waves, and Sleep Rhythms in EEG**

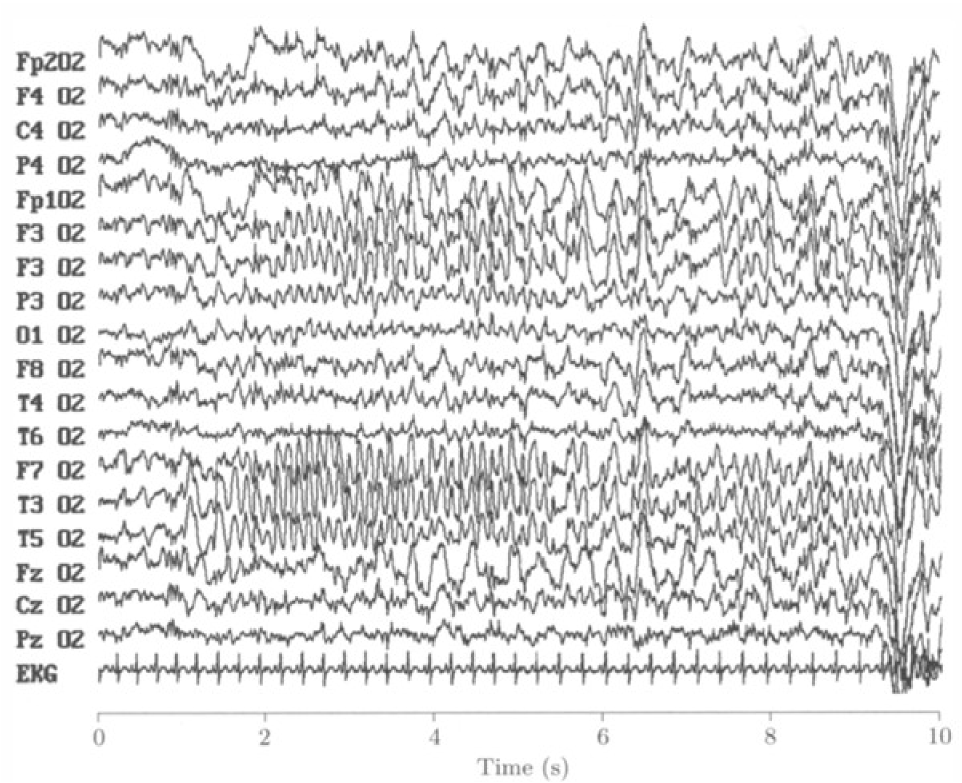
- **Spikes and Sharp Waves (SSWs)**:
  - **Transient waveforms** distinct from the background EEG
  - Occur with **irregular, unpredictable timing** (paroxysmal activity)
  - Often observed in **epileptic patients**
  - Typically occur **between seizures** → termed **interictal activity**
- **Waveform characteristics**:
  - Both feature a **steep initial upstroke**
  - Differentiated by **duration**:
    - **Spikes**: 20–70 ms
    - **Sharp waves**: 70–200 ms
  - Morphology is usually **monophasic**, but **biphasic or triphasic** shapes can also occur
  - **Waveform shape and appearance depend on electrode location**
- **Spike-wave complexes**:
  - Composed of a **spike followed by a slow wave**
  - Occur as **isolated events** or **in runs**, with repetition rates of **<3 to 6** Hz
  - Different **repetition rates** may relate to specific **clinical conditions**
  - See **Figure 2.4** for an example
- **Artifacts**:
  - Non-neural activity, like **cardiac signals**, can mimic SSWs
  - The **QRS complex** of a heartbeat may resemble a spike in EEG recordings
- **Sleep Rhythms**:
  - Brain operates in **three main functional states**:
    1. **Awake**
    2. **Non-REM sleep**

3. **REM sleep**
    - A person cycles through **non-REM and REM sleep** several times each night
- **Non-REM sleep**:
    - Considered an **"idle" brain state**
    - Accompanied by **slow, large-amplitude EEG rhythms**
    - Indicates **high synchrony** among cortical neurons
    - Subdivided into **four distinct stages** based on **depth of sleep**
        - See **Table 2.1** for classification of sleep stages




## Transient EEG Patterns and Ictal EEG

- **Sleep-Related Transient Waveforms** (see **Table 2.1** and **Figure 2.5**):
    - **Vertex waves**:
        - Occur in **early sleep stages**,
        - Triggered by **external stimuli** (e.g., sounds).
    - **Sleep spindles**:
        - Appear as **bursts of alpha-like activity**,
        - Duration: **0.5–1 second**.
    - **K complexes**:
        - Viewed as a **fusion of sleep spindles and vertex waves**.
- **REM Sleep Characteristics**:
    - EEG resembles **wakeful brain activity**, often showing **beta rhythms**,
    - Associated with **dreaming**,
    - **Eye movements** (with closed lids) occur **rapidly and irregularly**,
        - Produce a **sawtooth pattern** in the EEG when electrodes are **near the eyes**.




- **Ictal EEG** (during epileptic seizures):
  - Characterized by **abnormal rhythmic activity** with a **sudden amplitude increase** (see **Figure 2.6**),
  - Seizure onset often causes a **sudden frequency shift**, which may evolve into a **spiky wave pattern**,
  - The **ictal EEG** varies **significantly between seizures**, making both **manual and automatic detection challenging**.
- **Figure 2.4**:
  - Shows a **multichannel EEG** with **spike-wave complexes** at a **3-Hz repetition rate**,
  - Each channel is derived from **two electrodes**, with placements defined by codes (see **Figure 2.7** for electrode layout).

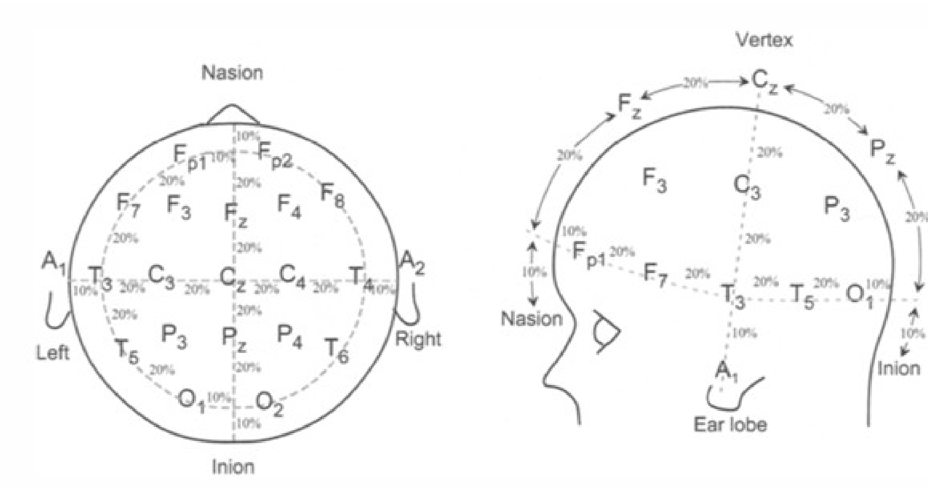
**Categories of EEG Activity Based on Nonstationarity and Sleep Stage Characteristics**

- **Table 2.1**: *Characteristics of Non-REM and REM Sleep Stages* [17]

| Sleep Stage | Sleep Depth | Waveforms |
|---|---|---|
| 1 | Drowsiness | Alpha dropouts to vertex waves |
| 2 | Light sleep | Vertex waves, sleep spindles, K complexes |
| 3 | Deep sleep | Much slowing, K complexes, some spindles |
| 4 | Very deep sleep | Much slowing, some K complexes |
| REM | REM sleep | Desynchronization with faster frequencies |

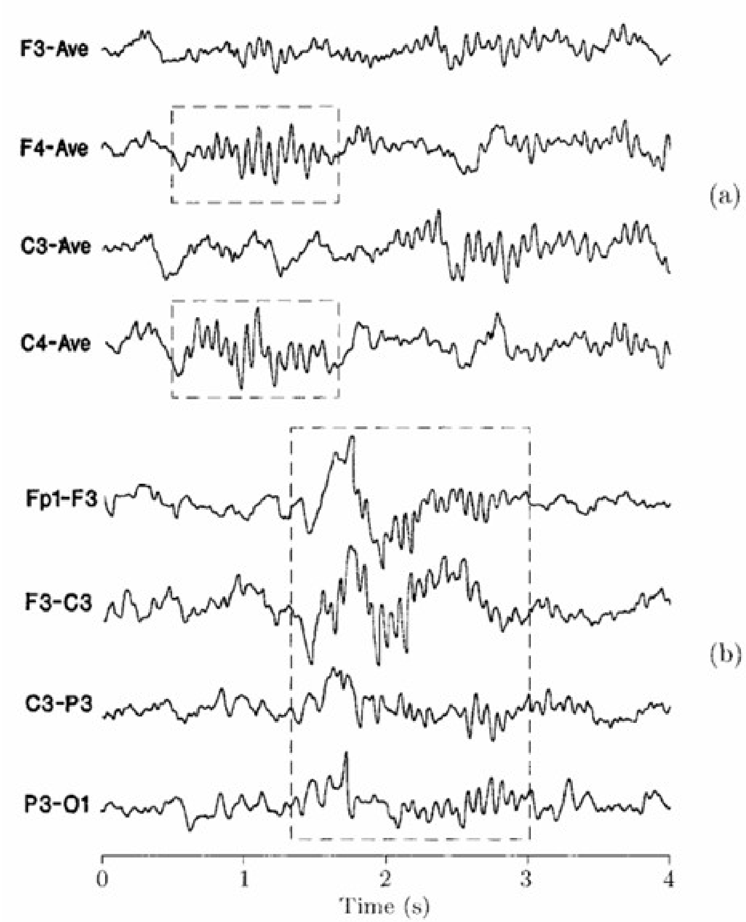
- **EEG Activity Categorized by Degree of Nonstationarity** (based on [18]):
  1. **Activity without major temporal changes**
     - Normal, spontaneous **waking activity at rest** (eyes open/closed),
     - Includes stable **alpha**, **beta**, and **theta rhythms**.
  2. **Slowly time-varying activity**
     - Observed during **sleep background** and **postictal states**,

- Includes **lengthy seizure discharges**.
3. **Intermittent activity**
   - Includes **intermittent slow rhythms** and **sleep spindles**,
   - Activity remains **stable over a few seconds**.
4. **Paroxysmal activity**
   - Includes **spikes**, **sharp waves**, **spike-wave complexes**, **3-Hz spike-wave formations**,
   - Also includes **K complexes** and **vertex waves** (typically during sleep),
   - Represents **transient, abrupt phenomena**.




## Electrode Placement and Spatial Resolution in EEG

- **Clinical EEG recordings** typically use the **International 10/20 system** [19], a **standardized electrode placement** method:
  - Utilizes **21 scalp electrodes**,
  - Positions are based on **anatomical reference points**,
  - The numbers **10** and **20** refer to **percentage distances** between electrode sites along the **skull perimeter** (see **Figure 2.7**).
- **Electrode types**:
  - **Bipolar electrodes**: measure potential differences between **two scalp sites**.
  - **Unipolar electrodes**: reference is taken from a **distant point** or the **average of all electrodes**.




- **Figure 2.5**:
  - Shows EEG recordings during sleep:
    - (a) **Sleep spindles**,
    - (b) **K complexes**, which are **fusions of a vertex wave and a sleep spindle**.
  - Reprinted from Wong [16].

- **Limitations of the 10/20 system**:
  - **Sparse spatial coverage**:
    - Average **interelectrode distance ≈ 4.5 cm** on an adult head.
  - Inadequate for **high-resolution brain mapping**.
- **EEG mapping**:
  - A **spatial analysis** technique that projects EEG activity as a **topographic map** on the scalp [20].
  - Using **too few electrodes** can lead to **spatial aliasing**, causing **inaccurate representations** of electrical activity.
- **Recommended electrode count for mapping**:
  - Studies suggest using **64 or more electrodes** to ensure **sufficient spatial detail** [21].

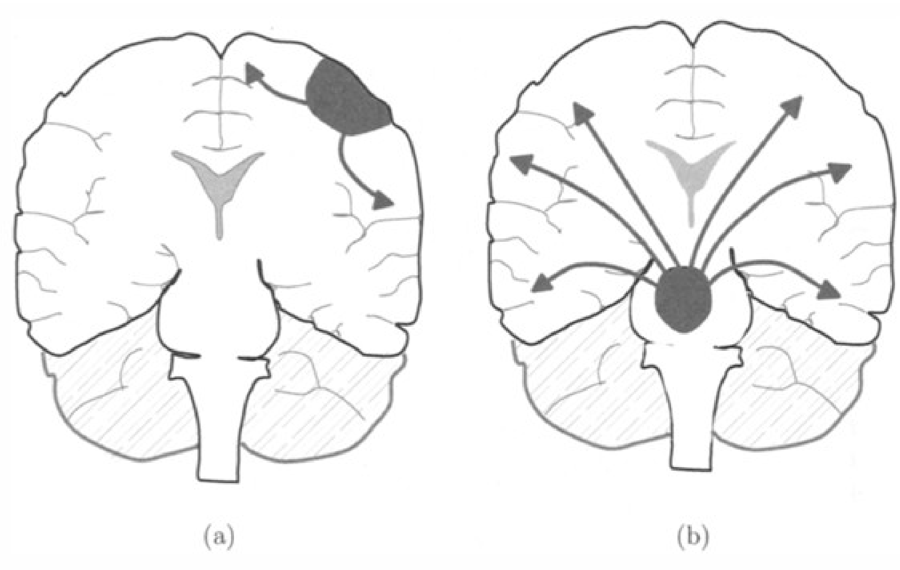
**EEG Sampling Rate Considerations**

- The **sampling rate** for **EEG signal acquisition** is typically set to **at least 200 Hz**,
  - This is based on the **frequency ranges** of standard **rhythmic brain activities**.
- However, for **detailed analysis** of **transient and evoked waveforms** (like **evoked potentials**),
  - A **much higher sampling rate** may be necessary.

- Further details are provided in **Chapter 4**, which discusses **EP signal analysis**.

**Clinical Applications of EEG**

- This section focuses on **two key clinical uses** of EEG:
    1. **Epilepsy diagnosis and monitoring**,
    2. **Sleep disorder analysis**.
- An additional, **research-oriented** application:
    - **Brain-computer interface (BCI)** development.
- **Figure 2.7**: *International 10/20 Electrode Placement System*:
    - Based on **anatomical reference points**:
        - **Nasion** (top of the nose),
        - **Inion** (back of the skull).
    - **Electrode labels**:
        - F = Frontal,
        - P = Parietal,
        - C = Central,
        - T = Temporal,
        - O = Occipital,
        - A = Auricle.
    - **Odd numbers** = left side,
      **Even numbers** = right side,
      **'z'** = midline.
- While the descriptions are **kept brief**, they highlight the **importance of signal processing** in **EEG-based clinical and research applications**.
- For deeper insights, readers are encouraged to consult **specialist literature**.

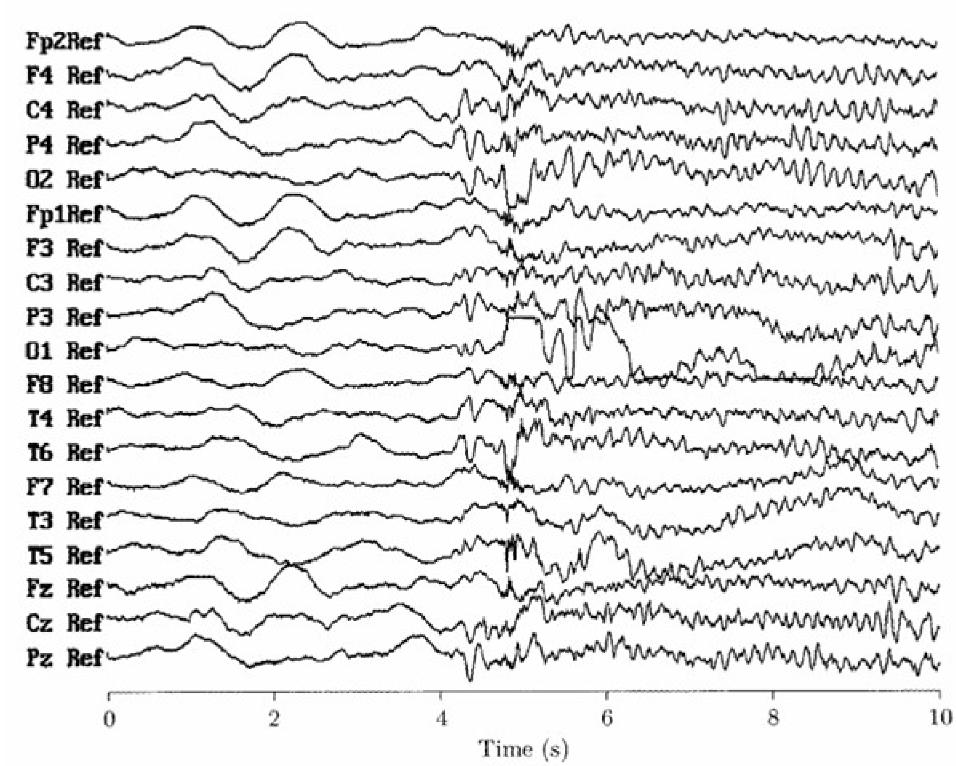



- **Figure 2.8**:
    - **(a) Partial seizure**:
        - **Focus in motor cortex**,
        - Symptoms: **arm muscle twitches**, patient remains **conscious**.
    - **(b) Primary generalized seizure**:
        - **Affects entire brain**,
        - Symptoms: **spasms** and **loss of consciousness**.
    - Diagrams show **frontal cross-sections of the brain**.

**EEG in Epilepsy Diagnosis and Seizure Classification**

- **Epilepsy** is characterized by **seizures**—sudden bursts of **uncontrolled electrical activity** in groups of **neurons** in the **cerebral cortex**.
- The **manifestation of a seizure** depends on:
  - The **location of the epileptic focus** (the impaired group of neurons),
  - How **other brain regions** become **recruited** during the seizure.
  - Example: A seizure starting in **sensory areas** may result in **visual or auditory sensations**.
- **Normal brain activity** relies on a balance between:
  - **Excitatory signals** (promote neuronal firing),
  - **Inhibitory signals** (suppress firing).
- **Imbalance between excitatory and inhibitory activity** is a key factor in epilepsy:
  - Often caused by **neurotransmitter dysfunction**:
    - **Too much excitatory activity**, or
    - **Too little inhibitory activity** increases seizure likelihood.
  - **Antiepileptic drugs** aim to **restore balance** by:
    - **Reducing excitatory activity**, or
    - **Enhancing inhibitory activity**.

- **Seizure symptoms** range widely:
  - Some may cause only **minor mental confusion**,
  - Others may lead to **loss of consciousness**,
  - Seizures vary in **frequency** (from rare to multiple per day),
  - Duration: typically **a few seconds to a few minutes**.
- **Seizure Classification** (based on EEG characteristics) [22]:
  - **Partial (focal) seizures**:
    - Start in a **specific area** of the brain,
    - Related to a **single epileptic focus**,
    - Can sometimes be **surgically treated** by removing the affected cortical region,
    - May evolve into generalized seizures → called **partial seizures with secondary generalization**.
  - **Primary generalized seizures**:
    - **Involve the entire brain** from the onset,
    - Not linked to a single focal point (see **Figure 2.8**).




- **Figure 2.9**:
  - Displays an **EEG recorded during the onset** of a **primary generalized seizure**,
  - Shows characteristic **sudden changes in amplitude and frequency**.

**EEG in Clinical Epilepsy Diagnosis and Activation Techniques**

- **Causes of Epilepsy**:
  - Linked to various **pathological conditions**, including:
    - **Brain injury**,
    - **Stroke**,
    - **Brain tumors**,
    - **Infections**,
    - **Genetic factors**.
  - In **most patients**, the **cause is unknown**.

- **EEG: Primary Tool for Epilepsy Diagnosis**:
  - Used to **determine seizure type and origin**.
  - Standard procedure:
    - **30-minute EEG recording** in a **quiet, dimly lit room**.
    - Patient is asked to **open and close their eyes** to observe EEG changes (e.g., **alpha rhythm variations**, see p. 34).
- **Activation Methods** to **provoke epileptic waveforms**:
  1. **Hyperventilation** – patient breathes **rapidly and deeply**.
  2. **Photic stimulation** – patient exposed to **flashing strobe light** (1–25 Hz).
  3. **Sleep deprivation** – sometimes used to enhance detection of seizure-prone activity.

- **Interictal EEG** (recorded **between seizures**):
  - May still show **epileptiform waveforms** indicating **seizure tendency**.
  - Examples:
    - **Spike and sharp waves (SSWs)** in a **localized brain area** (e.g., left temporal lobe) suggest **partial seizures**.

        - **Bilateral spike-wave complexes** across hemispheres suggest **primary generalized seizures**.
    - However, **absence of interictal abnormalities does not exclude epilepsy**.

**Prolonged EEG Monitoring: Video and Ambulatory EEG**

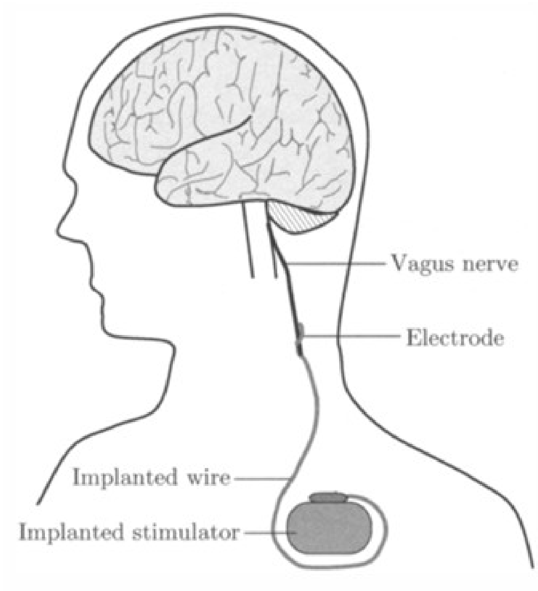
- **Seizure EEG recording** often requires **long-term monitoring**, as seizures may not occur during short clinical sessions.

- **Video EEG**:
    - Conducted **in-hospital over several days**,
    - Combines **EEG recordings** with **video footage** of the patient,
    - Enables neurologists to **correlate EEG changes** with **visible seizure behavior**,
    - Improves **accuracy in seizure assessment**.
- **Ambulatory EEG**:
    - A **more convenient and cost-effective** alternative,
    - Recorded during the patient's **normal daily life** using a **small digital recorder** (worn around the waist),
    - Typically done for **24 hours or more**,
    - Captures both **waking and sleeping states**.

- **Practical considerations**:
    - Requires **multiple electrodes** attached to the scalp for extended periods,
    - May cause **itching**, leading to **scratching**, which introduces **noise artifacts**,
    - **Other noise sources** include:
        - **Blinking**,
        - **Frowning**,
    - These artifacts can **mimic physiological waveforms**, making **EEG interpretation more challenging**.

**Long-Term EEG Monitoring and Therapeutic Interventions for Epilepsy**

- **Long-term EEG monitoring** (hospital or ambulatory) generates **large volumes of data**, making manual review **time-consuming**.
- **Automatic spike and seizure detection** is critical for:
    - **Reducing data load**,
    - **Enhancing interpretation efficiency**.
- Detection algorithm design requires:
    - **Signal processing techniques** for **mathematically characterizing**:
        - **Interictal waves**, and
        - **Seizure patterns** [24–26],
    - **Noise and artifact rejection algorithms** are also essential.
- **Seizure prediction/warning algorithms**:
    - Can provide **early alerts** to patients wearing **ambulatory devices**,
    - Allow patients to take **safety precautions** before a seizure occurs.




- **Therapeutic Devices**:
  - Aim to **prevent seizures before they start**.
- **Vagus Nerve Stimulator (VNS)**:
  - **Most well-known** device in this category [27],
  - Delivers **intermittent electrical pulses** to the **vagus nerve**,
  - Has shown **antiepileptic effects** in some patients, though **mechanisms remain unclear**.
  - **Implanted surgically**, like a **cardiac pacemaker**,
    - **Stimulating electrode** is wrapped around the **vagus nerve in the neck** (see **Figure 2.10**).
- **Current VNS limitations**:
  - Operates **blindly** using **preset stimulation patterns**,
  - Does **not adapt to actual seizure risk** in real-time.
- **Future development**:
  - Focuses on **intelligent VNS systems**,
  - Will incorporate **seizure prediction algorithms** using **advanced signal processing** [28, 29].

**Classification of Sleep Disorders**
Sleep disorders are common and may arise from **medical or psychological causes**. A widely used classification scheme organizes them into **four main groups** [30]:

1. **Insomnia**
   - **Difficulty initiating or maintaining sleep**.
   - Commonly experienced during **stressful events** (e.g., exams), often **temporary** and **not treated**.
   - Associated conditions:
     - **Depression** → reduces **deep sleep** (Stages 3 & 4), leading to **daytime fatigue**.
     - **Alcohol or drug abuse** → disrupts sleep patterns.

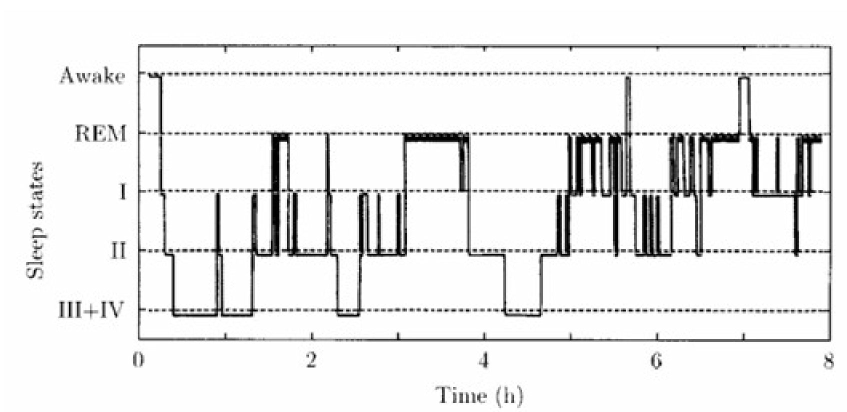
1. **Hypersomnia**
   - Characterized by **excessive sleepiness** and **daytime somnolence**.
   - Examples:
     - **Narcolepsy**: sudden, **uncontrollable daytime sleep attacks**, despite **normal night-time sleep**.

- **Sleep apnea**:
  - Involves **frequent breathing interruptions** during sleep (>10 seconds),
  - Causes **snoring-induced awakenings**,
  - Results in **disrupted deep sleep** and **severe daytime fatigue**,
  - May also be considered a form of **insomnia**.

1. **Circadian Rhythm Disorders**
   - Affect the **timing of sleep-wake cycles**.
   - Examples:
     - **Jet lag**:
       - Caused by **travel across time zones**,
       - Leads to **temporary misalignment** of the body clock,
       - Symptoms usually **resolve within a week**.
     - **Non-24-hour sleep-wake disorder**:
       - Diurnal rhythm is slightly **longer than 24 hours**,
       - Patient's sleep onset **shifts later by ~30 minutes daily**,
       - Leads to **cycling into and out of daytime sleep**, making **stable routines difficult**.

**Parasomnia and Automated Sleep Staging**

- **Parasomnia**: Sleep disorders involving **abnormal behaviors or experiences** during sleep, often **without full awakening**.
  - **Nightmares**:
    - Involve **threatening dream content**,
    - Associated with **increased autonomic activity**, such as a **sudden spike in heart rate**.
  - **Sleep terrors**:
    - Not linked to dreams,
    - Marked by **piercing screams or cries**,
    - Primarily seen in **children**, typically **resolves with age**.
  - **Sleepwalking**:
    - Occurs during **deep sleep stages**,
    - Often **related to sleep terror**, involving **unconscious motor activity**.




- **EEG in Sleep Disorder Diagnosis**:
  - Each type of sleep disorder has **distinct EEG manifestations**,
  - Accurate diagnosis requires **quantitative tracking** of **sleep stage patterns** over time (see **Figure 2.11**).
- **Sleep study setup**:

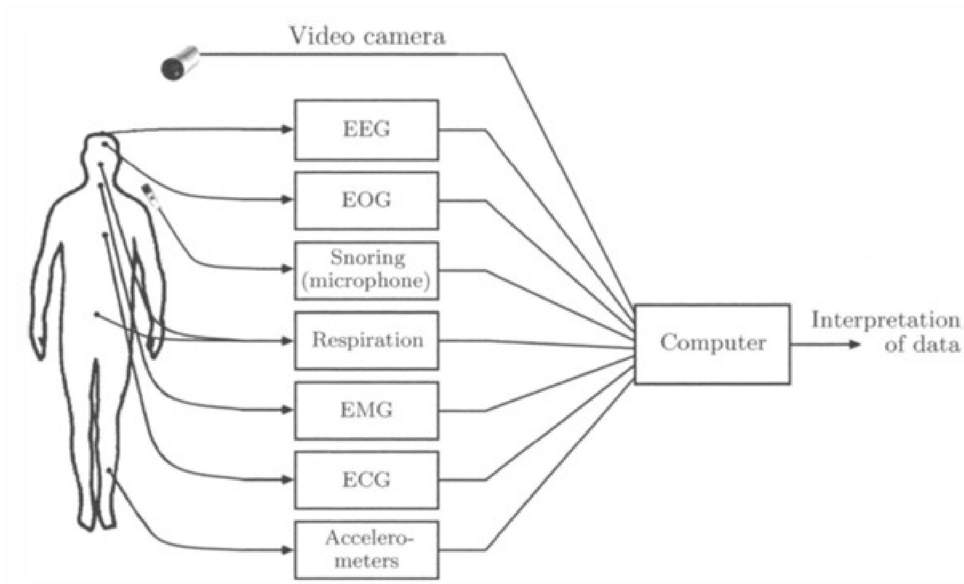
    - Patients stay **overnight in a sleep lab**,
    - **Scalp electrodes** are used to record the EEG.

- **Need for Automation**:
    - **Manual sleep staging** is **labor-intensive**,
    - There is a strong need for **automated systems** that can:
        - Detect **individual sleep waveforms** (e.g., **vertex waves**, **sleep spindles**, **K complexes**),
        - Identify different **rhythms** (e.g., **delta**, **theta**, **alpha**, **beta**).
- **Design of an automated system** should:
    - **Mimic neurologist interpretation**,
    - Account for both:
        - **Spatial distribution** of waves across EEG channels,
        - **Temporal distribution** within each channel [31, 32].

**Polysomnography and Automated Sleep Analysis**

- **Sleep analysis** is typically performed using **polygraphic recordings**, which include **multiple physiological signals**—not just EEG.
- These recordings are known as **polysomnographic** recordings.

- **Figure 1.8** (Introduction) illustrates a polysomnographic setup with signals including:
    - **EEG** (brain activity),
    - **ECG** (heart activity),
    - **EMG** (muscle activity),
    - **EOG** (eye movements),
    - **Blood pressure**,
    - **Nasal and abdominal respiration**.




- **Polysomnography** may also include:
    - **Video recording** of the patient during sleep,
    - Used to observe **behavioral expressions**, such as **sounds** and **body movements** (see **Figure 2.12**).

- **Challenges and Solutions**:

    - Analysis is **complex** due to the **variety of signals** from different physiological sources.
    - **Computer-based analysis** helps to:
        - **Handle complexity**,
        - **Quantify correlations** between signals (e.g., between EEG patterns and respiratory changes).
    - **Noise and artifact rejection** is as essential here as it is in systems for **automatic seizure detection** [33, 34].

**Brain-Computer Interfaces (BCIs) and EEG-Based Communication**

- A **Brain-Computer Interface (BCI)** enables communication and control of the **external world** without involving **peripheral nerves or muscles** [35–37].
- Instead of muscle-based outputs like **speech** or **writing**, communication is achieved through:
    - **Spontaneous** or
    - **Evoked EEG activity**.

- **Primary beneficiaries** of BCI systems:
    - Individuals with **severe neuromuscular disorders**,
    - Especially those with **complete paralysis** (e.g., **locked-in syndrome**),
    - BCIs can enable:
        - Use of **spelling programs**,
        - Operation of **neuroprosthetic devices**.
- **Development timeline**:
    - Concept introduced in the **early 1970s** [38],
    - Significant advances occurred in the **1990s**, driven by:
        - Better understanding of **EEG signals**,
        - Progress in **computer processing technology** [39, 40].

- **Two key components in BCI design**:
    1. The **user's mental process**:
        - Encodes **commands** within the **EEG signal**.
    2. The **BCI system**:
        - Uses **advanced signal processing** to:
            - **Analyze** EEG signal characteristics,
            - **Translate them into commands** for controlling an external device.

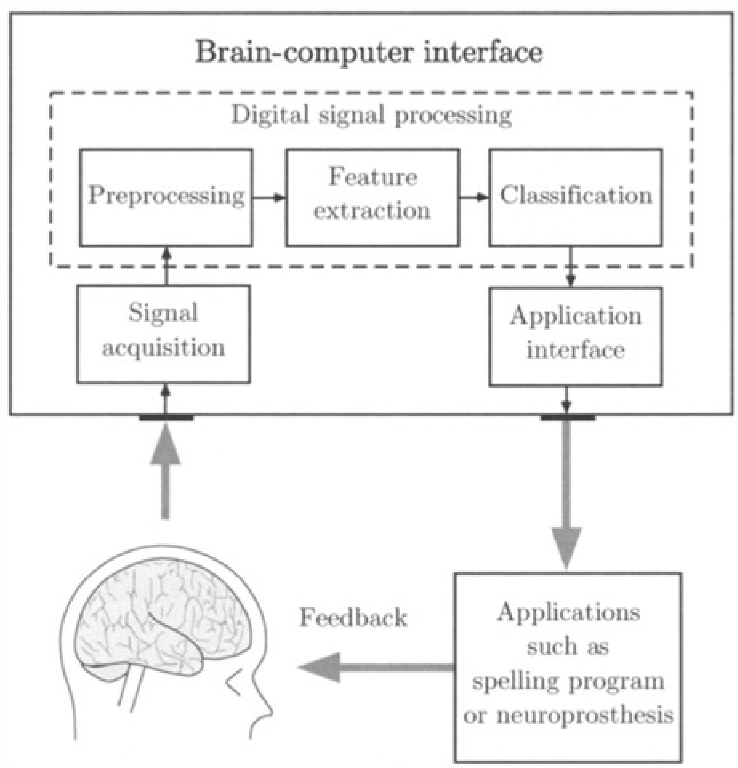
**Motor Imagery and Adaptation in Brain-Computer Interfaces (BCIs)**

- **Motor imagery**:
    - The **mental simulation of movement** (e.g., hand or foot),
    - Produces **distinct EEG patterns** that can encode **commands** [35, 40, 41],
    - No **actual muscle movement** occurs—only the **neural process** is activated.

- **BCI Learning Process**:
    - The subject is asked to **imagine specific movements**,
    - For each imagined action:
        - **Descriptive features** are extracted from the EEG,
        - These features are used to **train a classifier**,
    - **Repeated trials** enable the classifier to learn to **differentiate mental commands**.
- **Post-training use**:
    - The **classifier** translates **ongoing motor imagery** into **device commands** (e.g., selecting letters in a spelling program),

- The BCI must function in **real time**, so **signal processing must be fast**, without **unacceptable delays**.

- **Continuous Adaptation**:
    - **BCI training is not permanent**—must be **repeated regularly**,
    - EEG signals vary with:
        - **Time of day**,
        - **Hormonal levels**,
        - **Fatigue**,
    - The **classifier must be updated** to maintain **accurate performance**.
- **Two adaptive controllers** must coordinate:
    1. The **user's brain** (intention and control),
    2. The **BCI system** (signal feature extraction and classification),
    - **Success** depends on:
        - The user's ability to produce **controllable EEG features**,
        - The BCI's ability to **correctly interpret** those features [36].




- **Figure 2.13**
    - Presents a **block diagram** outlining the **main components of a BCI** system.

**Feature Extraction for BCIs Using Spectral Analysis**
- The **most common method** for feature extraction in BCI systems is **spectral power analysis** across different **EEG frequency bands** [42–46].
- While **single-channel spectral analysis** can be useful, **multichannel analysis is preferred** because it:
    - Captures **spatial variations** in EEG signals,
    - Exploits differences between **brain hemispheres**, which are relevant in **motor imagery tasks** [47].

- **Key EEG rhythms used in BCIs**:

- **Mu rhythm** and
    - **Beta rhythm**,
    - Both originate from the **sensorimotor cortex**—the region responsible for **hand and foot movement control**.
- The **selection of frequency bands** focuses on capturing these **task-relevant rhythms**.
- **Further details**:
    - **Spectral feature extraction techniques** used in BCI systems are discussed in **Chapter 3**.

**BCI Performance and Alternative Approaches**

- **BCI performance** is commonly evaluated using the **information transfer rate**, measured in **bits per minute**.
    - This depends on how accurately the system can **classify different mental (imagined) states**.
- **Current BCI capabilities**:
    - Achieve about **10–25 bits/minute**,
    - Enables **paralyzed users** to write around **two words per minute**,
    - Still **too slow** for:
        - **Controlling complex movements**,
        - **Operating neuroprosthetic devices** effectively.
- **Potential performance enhancement**:
    - Using **surgically implanted microelectrodes**,
    - Allows recording from **more localized neuron populations**,
    - Can **significantly boost information transfer rates**.

- **Alternative BCI design**:
    - Instead of analyzing **spontaneous EEG**, BCIs can use **evoked potentials (EPs)**,
    - EPs are EEG responses triggered by **sensory stimulation** [36, 38, 48–50].