Neural Engineering study guide

Basic neuroscience:

* Nervous system anatomy
  + Central and peripheral nervous system
  + Divisions of peripheral nervous system
    - Autonomic –> sympathetic (fight or flight) and parasympathetic (rest and digest)
    - Somatic (skeletal muscle control)
    - Enteric (digestion)
  + Divisions of central nervous system
    - Brain
    - Spine
    - Retina
* Brain anatomy
  + Cortex (layered neurons) vs. subcortex (unlayered)
  + Reason for wrinkles (to increase surface area)

|  |  |  |
| --- | --- | --- |
| *Area* | *Major subregions* | *Major functions* |
| Frontal lobe | Prefrontal, premotor, supplementary motor, primary motor | Executive functions, short term memory, movement planning and execution |
| Parietal lobe | Primary and secondary somatosensory, sensory association | Somatosensory, proprioception, pain, sensory association, visual movement |
| Temporal lobe | Temporal cortex, medial temporal cortex, hippocampus | Long term memory formation and storage, language comprehension |
| Occipital lobe | V1, V2, V3, V4 (Add’l vision: MT in temporal, V6 in parietal) | Visual processing |
| Insula | N/A for this class | Emotions, pain (emotional and physical), taste, motivation, consciousness |
| Limbic system | Hippocampus, hypothalamus, amygdala, cingulate, parts of medial temporal, and more | Emotion, motivation, long-term memory |
| Basal ganglia | Striatum (putamen and caudate), globus pallidus, substantia nigra, subthalamic nucleus, nucleus accumbens | Movement refinement |
| Thalamus | Many nuclei | Sensory relay |
| Hypothalamus | Many nuclei | Homeostasis and the four F’s |
| Brainstem | Midbrain, pons, medulla | Basic physiological functions |
| Cerebellum | N/A for this class | Movement refinement, balance, more? |

Sensory systems

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| *Organization* | Retinotopic (spatial) | Tonotopic (frequency) | None | Somatotopic (spatial/body part) | Somatotopic (spatial/body part) | Somatotopic (spatial/body part) |
| *Primary sensory area* | Occipital, also dorsal (parietal) and ventral (temporal) streams | Superior temporal lobe | Cerebellum, brainstem | Primary somatosensory (parietal) | Primary somatosensory (parietal), cerebellum | Primary somatosensory (parietal), insula, anterior cingulate |
| *Path to brain* | Optic nerve to optic chiasm (crosses) to thalamus to optic tract | Cochlear nerve to brainstem (crosses) to thalamus to cortex | Vesibular nerve to brainstem to brain and body (vestibulospinal tract) | Peripheral nerve to dorsal roots to own spinal tracts to thalamus to cortex | Peripheral nerve to dorsal roots to own spinal tracts to thalamus to cortex | Peripheral nerve to dorsal roots to own spinal tracts to thalamus to cortex |
| *Sensors* | Rods and cones (rhodopsin) | Inner hair cells on basilar membrane | Hair cells (in semicircular canals, endolymph. In macula, otoliths) | Ruffini’s, Meissner’s, Pacinian, Merkel’s, hair follicles | Muscle spindles, Golgi tendon organs | Free nerve endings + context from touch, temperature, proprioception |
| *Sensory organ* | Retina | Cochlea | Semicircular canals, macula | Skin | Muscles, connective tissue | Skin, muscles, connective tissue, viscera |
|  | *Vision* | *Hearing* | *Vestibular* | *Touch* | *Proprioception* | *Nociception* |

Motor systems

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| --- | --- | --- |
| *Area* | *Job* | *Side (relative to muscle)* |
| Premotor | Movement planning | Contralateral |
| Supplementary motor | Bilateral coordination, stabilization and posture | Contralateral |
| Primary motor | Initiate and send out motor commands | Contralateral |
| Basal ganglia | Refine motor commands | Contralateral |
| Cerebellum | Refine motor commands, balance | Contralateral |
| Brainstem | Decussate, reorganize, introduce non-cortical info | Decussation in medulla |
| Lateral corticospinal tract | Carry primary motor command information | Ipsilateral |
| Other spinal tracts | Carry ancillary info, such as balance adjustment | Ipsilateral |
| Neuromuscular junction | Convert from neural signal to muscle signal | Ipsilateral |
| Muscles | Contract and release in opposing groups to move limb (e.g., bicep and triceps) | Ipsilateral |

Neuron physiology

|  |  |
| --- | --- |
| *Neuron part* | *Job* |
| Dendrite | Receive signals from other neurons; ranges from 1 to hundreds of thousands per neuron, usually ~1000 |
| Neurotransmitter receptors | Located on dendrites, are activated by neurotransmitters released by other neurons |
| Soma/cell body | Perform normal cellular functions, including metabolism and neurotransmitter manufacture |
| Nucleus | Contains DNA |
| Cell membrane | Boundary of cell, including maintaining gradient of ions and source of electrical potential |
| Ion channels | Allow ions (mainly sodium, potassium, calcium) in and out of neuron, create changes in electrical properties by adjusting ion concentrations |
| Myelin | Fatty wrapper around axon that helps maintain electrical potential of membrane with less work |
| Axon | Long, skinny path connecting cell body to axon terminals, may branch but only one exits cell body |
| Process | Axon, dendrite, or for unipolar cells the combined dendrite/axon complex |
| Axon terminals | The ends of the axons, where electrical signal is translated into neurotransmitter release. Ranges from 1 to thousands per cell |
| Neurotransmitter | Chemicals that have an effect on other neurons through direct release onto other cell |
| Vesicles | Membrane packets containing neurotransmitter that are released at axon terminal |
| Synapse | Location where two neurons meet, about 20nm wide, approx. 100-500 trillion in adult human |
| Hormone | Molecule that impacts brain or body that travels through blood |

Neuron communication

* How do neurons use electricity (within cell – generated by ion gradients) vs. chemicals (between cells – neurotransmitter release)
* Neuroplasticity – what changes?
  + Presynaptic cell
    - Amount of neurotransmitter released
    - Probability of neurotransmitter release (easier or harder to trigger)
  + Postsynaptic cell
    - Type of neurotransmitter receptor
    - Sensitivity of neurotransmitter receptors
    - Number of neurotransmitter receptors
  + Both
    - Presence of a new synapse
  + NOT growing a new neuron!
* What triggers neuroplastic changes to synapses?
  + Cells activate one after the other repeatedly
  + Electrical stimulation
  + Cells NOT activated simultaneously – connection weakens

Measuring and stimulating the nervous system

|  |  |  |  |
| --- | --- | --- | --- |
|  | Measures | Benefits | Drawbacks |
| MRI | Blood flow | High spatial resolution, whole brain, non invasive | Giant magnet, poor time resolution, expensive, no stimulation |
| Electroencephalography | Approx. millions of neurons | Inexpensive, non-invasive, good time resolution | Poor spatial resolution, poor signal quality, only brain surface, no stimulation |
| Electrocorticography | Approx. 500,000 neurons | Good time and space resolution, minimally invasive, can stimulate | Only part of brain, only currently used with atypical brains, spatial resolution not good enough |
| Penetrating microelectrode | Approx. thousands of neurons | Best time and space resolution, can stimulate | Only tiny part of brain, causes damage |
| Nerve cuff | Approx. thousands of peripheral axons | Inexpensive, minimally invasive, can stimulate | Only works if surviving peripheral nerves present |

How do we ensure measurement and stimulation are safe and ethical?

* Safety – implantation and long-term use
* Security and privacy concerns
* Informed consent
* Equitable access
* Assistance vs. augmentation
* Maintenance and degradation

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| --- | --- | --- | --- | --- | --- | --- | --- |
| *Treatment – current and engineering options* | Occ. or phys. therapy, BCI, mobility aid, exoskeleton | L-dopa, deep brain stimulator | Mobility aids, palliative, BCI | Mobility aids, experimental anti-autoimmune treatments | Prosthetics (with different control systems) | BCI for rehab, weakness, or paralysis | Exoskeleton or orthotic, BCI |
| *Effect - motor* | Partial to complete loss in affected area | Tremor, uncoordinated movement, difficulty starting/stopping | Weakness, then paralysis, over entire body | Intermittent weakness and partial paralysis, esp. shuffling gait | May cause poor balance | If in motor area, may cause reduced function | Weakness or paralysis, poor coordination |
| *Effect - sensory* | Partial to complete loss in affected area | Usually none | None – typical sensation | Itches, tightness in chest, pins and needles, numbness | Phantom limb, sometimes painful | If in sensory area, loss of function | None – typical sensation |
| *Area affected* | Varies by injury, not head and face | Body, especially walking and hand movements | Whole body, including head and face | Whole body, to varying degrees, especially gait | Varies | Varies in brain and spinal cord | All skeletal muscles |
| *Defining symptoms* | Paralysis (complete or partial), loss of sensation | Tremor, uncoordinated, difficulty starting and stopping | Weakness, then paralysis | Intermittent weakness, partial paralysis, progressive | Missing limb or part of limb | Loss of consciousness, confusion, sometimes weakness or numbness | Weakness or paralysis, poor muscle tone and coordination |
| *Most common causes* | Accident, stroke, cancer | Death of substantia nigra neurons (sometimes genetic, sometimes not) | Death of skeletal muscle motor neurons | Autoimmune response against glia making myelin | Accident, cancer, congenital | Clot/burst vessel causing lack of blood to part of brain | Group of disorders causing breakdown or weakness of skeletal muscles |
| *Problem* | Spinal cord injury | Parkin-son’s | Amyo-trophic lateral sclerosis | Multiple sclerosis | Amputation | Stroke or aneurysm | Muscular dystrophy |

Components of a BCI (all BCIs have at least some of these, some have all of them

* Sensors – environment
* Sensors – own body (i.e., proprioception)
* Electrodes in central or peripheral nervous system
  + May record and/or stimulate
* Computer, with software
  + Processes input from sensors and/or intent from nervous system
  + Must be adjustable
* Power source
* End effector – what user controls
* Case, carrier, or implant

Specific design considerations for neural engineering

* Level of invasiveness
* Size of processor, electrodes
* What to measure, with what tool
* What to stimulate, with what tool, in what pattern
* Heat generation
* Power source – longevity, replacement
* Security (hacks, bugs)
* Maintenance of engineered system and long-term care for user
* Equitable access
* Where will processing unit go in body?
* What is a difficult problem for computers to solve?
* Why is sensory function not optional?

Bidirectional neural engineering

* Motor designs
  + Prosthetic – replace lost limb
  + Orthotic – augment weak or paralyzed limb
  + External robotic limb
  + Wheelchair (superior control)
  + Computer/cursor/keyboard control
* Sensory designs – where do they stimulate? What do users perceive? Who is eligible?
  + Retinal implants
  + Cochlear implants
  + Vestibular implants
  + Cortical, spinal, peripheral nerve stimulation – currently touch and proprioception
* What do illusions demonstrate about sensation and perception?