



Biochemistry of neurotransmitters

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Neuroscience

Resources



- This lecture
- Mark's Basic Medical Biochemistry, 4th ed, pp. 908-918
- <http://what-when-how.com/neuroscience/neurotransmitters-the-neuron-part-1/>



Definition of a neurotransmitter

- A neurotransmitter is a chemical substance that is:
 - synthesized in a neuron,
 - released at a synapse following depolarization of the nerve terminal (usually dependent on an influx of calcium ions),
 - which binds to receptors on the postsynaptic cell and/or presynaptic terminal
 - to elicit a specific response.

Characteristics of a neurotransmitter



- A chemical substance that:
 - Is synthesized and stored in a presynaptic neuron (the enzymes needed for its synthesis must be present in the neuron),
 - Is released at a synapse following depolarization of the nerve terminal (usually dependent on an influx of calcium ions),
 - binds to receptors on the postsynaptic cell and/or presynaptic terminal,
 - elicits rapid-onset and rapidly reversible responses in the target cell,
 - Is removed or inactivated from the synaptic cleft.



Types of neurotransmitters

- Small-molecule neurotransmitters
 - Biogenic amines (epinephrine, dopamine, histamine, serotonin)
 - Amino acids (GABA, glutamate, aspartate, glycine)
 - Acetylcholine
 - Purines (ATP)
- Neuropeptides
- Gases (nitric oxide, carbon monoxide)

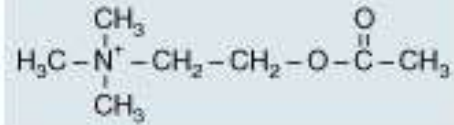
- Two or more transmitters (usually a small-molecule neurotransmitter and a neuropeptide) can coexist in neurons (e.g., most spinal motor neurons contain acetylcholine and calcitonin gene-related peptide).

Structures of neurotransmitters

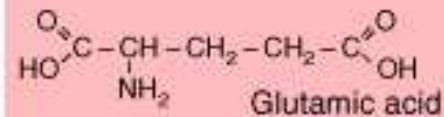
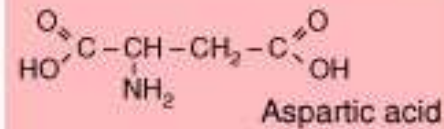
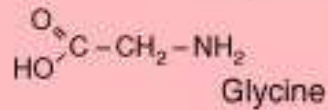
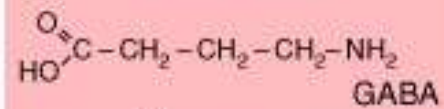


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Acetylcholine

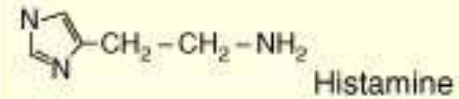
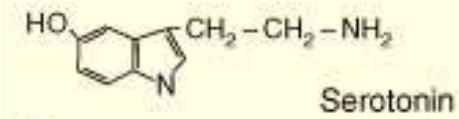
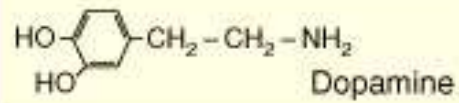
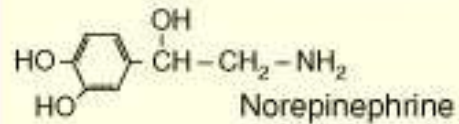
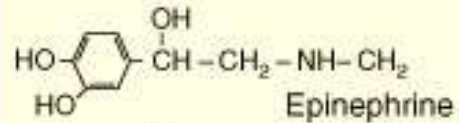


Amino acids

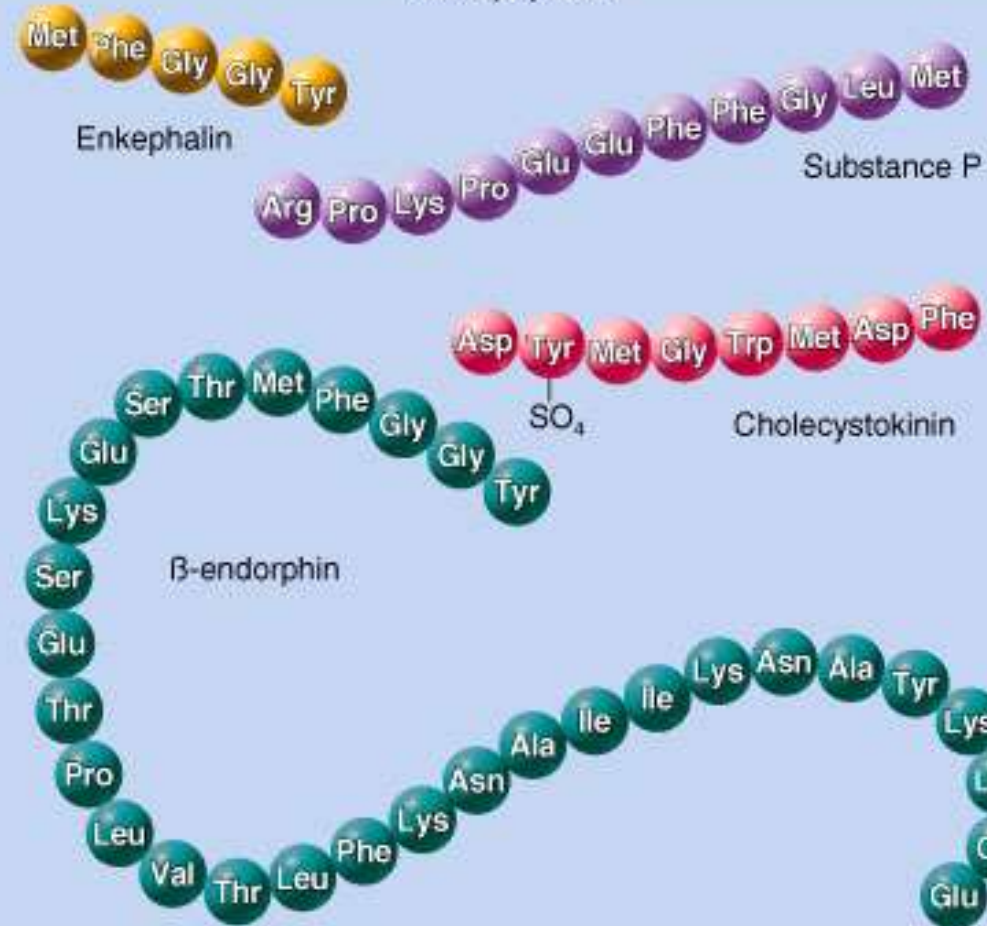


Monoamines

Catecholamines

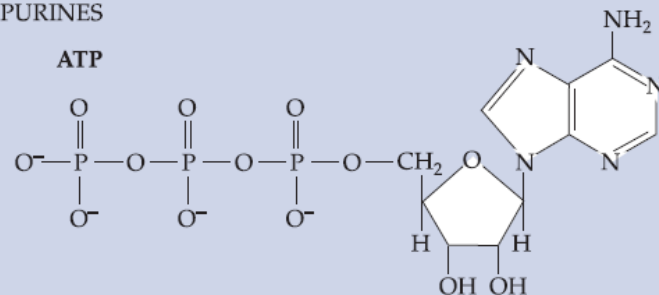


Neuropeptides



PURINES

ATP



Neuropeptides	Small-molecular neurotransmitters
Short-chain peptides (3-60 aa's), Large MW	Endogenous chemicals, Low MW
Slow-acting	Fast-acting
Slow response	Acute response
Prolonged action	Short-term response
Acts on several receptors	Acts on specific a receptor
Can change metabolism	Most do not change metabolism
Alter gene expression	Most do not change gene expression
Synthesized in the ER and Golgi apparatus	Synthesized in the cytosol of presynaptic nerves
Synthesized in low concentrations	Synthesized in high concentrations
Found allover the neuron	Found in the axon terminals of presynaptic neurons
Stored in large dense-core vesicles	Stored in small secretory vesicles
Released to the synaptic cleft along with another NT	Released individually
released at low cytosolic Ca^{2+} concentrations	released at high cytosolic Ca^{2+} concentrations
Have a different site of actions than their origin	Acts in direct apposition of to the releasing cell
Not re-taken up and not reused	Can be re-taken up and reused
Relatively more potent	Relatively less potent
Terminated when proteolytically degraded or diffused	Terminated by reuptake, taken up by glial cells, diffused, or enzyme degradation

LISTS OF NEUROPEPTIDES

[NEUROPEPTIDES | HUGO GENE NOMENCLATURE COMMITTEE](#)

[NEUROPEPTIDE GENE FAMILIES](#)

[LIST OF NEUROTRANSMITTER INHIBITORS AND NEUROPEPTIDES](#)

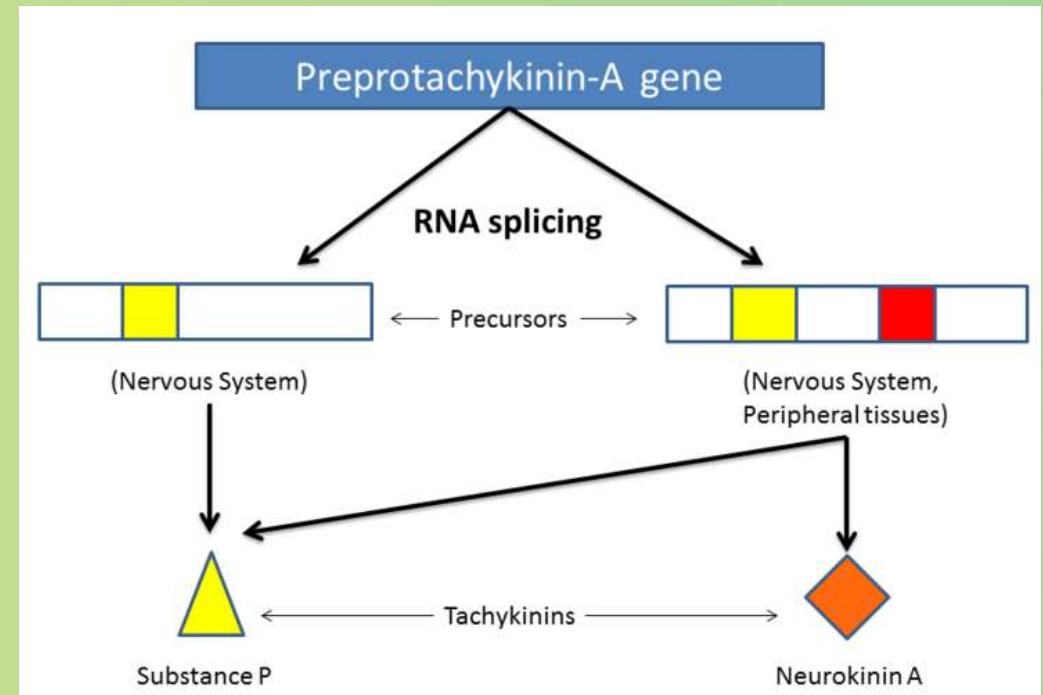
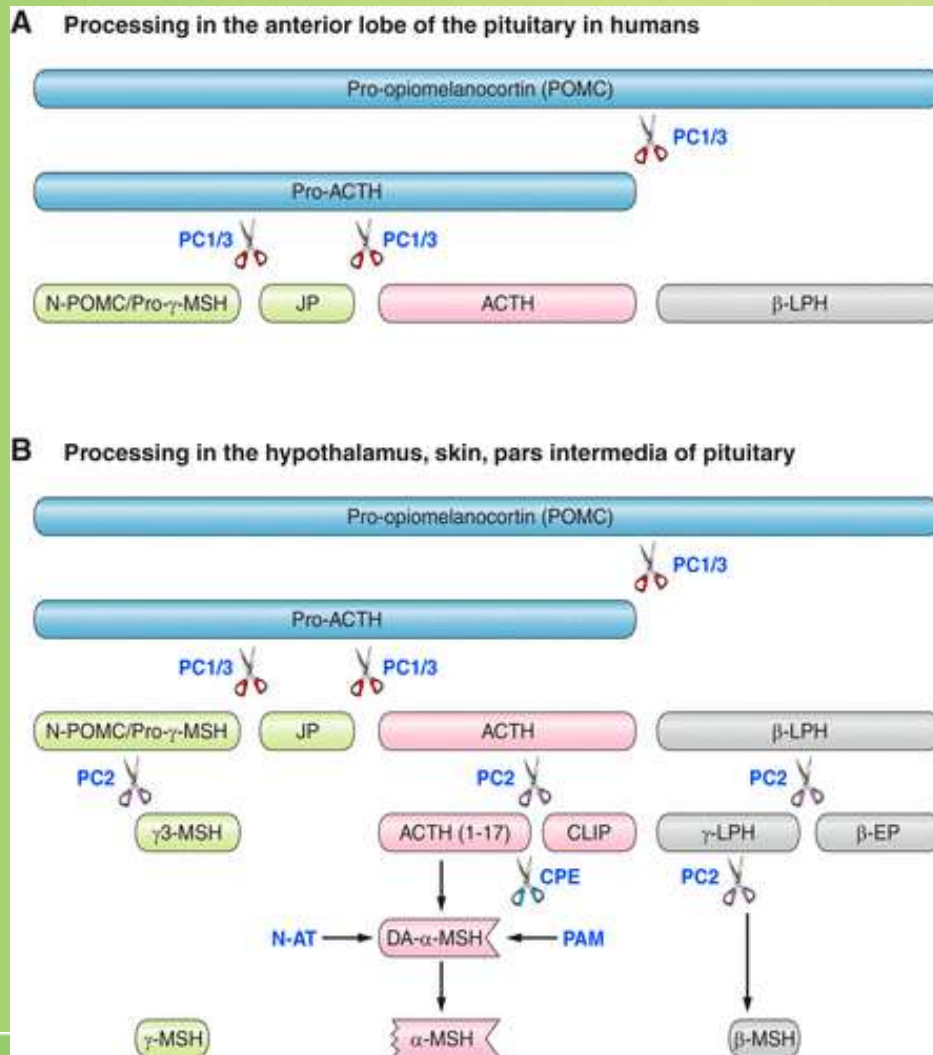
NEUROPEPTIDES



Some characteristics of neuropeptides

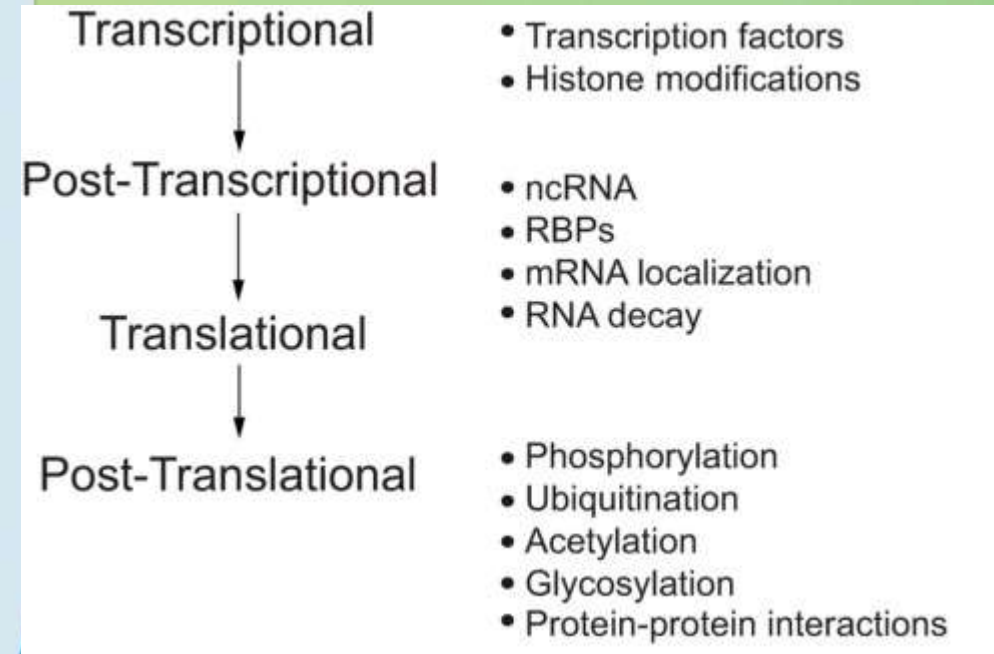
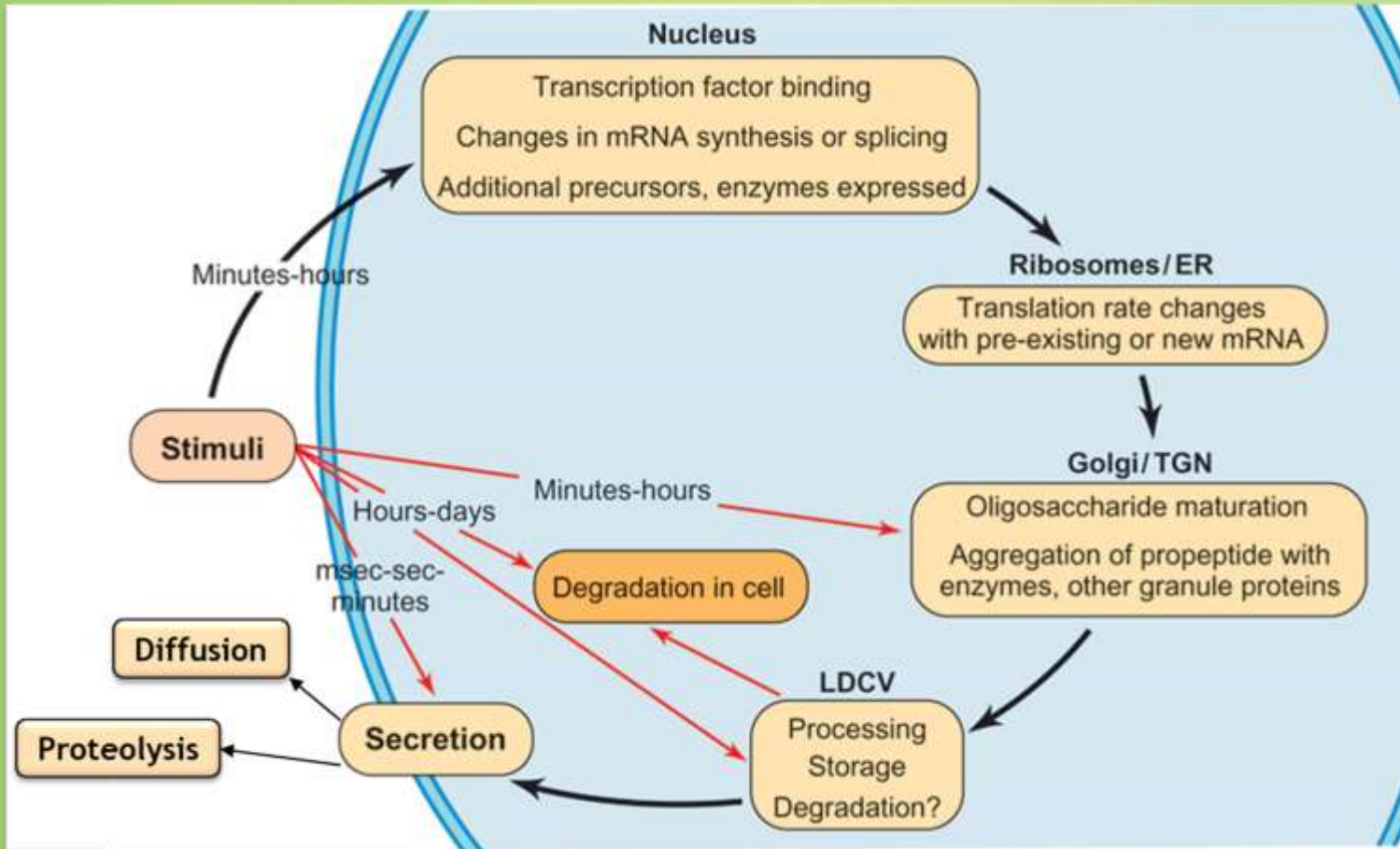
- More than 50 neuropeptides have been described affecting:
 - Behavior, pain perception, memory, appetite, thirst, temperature, homeostasis, and sleep
- They can be considered neurotransmitters or neurohormones.
- They are synthesized just like proteins are.
 - They are subject to alternative splicing and protein processing.
 - They can be tissue-specific.
 - Examples: substance P/neurokinin A and proopiomelanocortin

Do not memorize. Just enjoy the colors



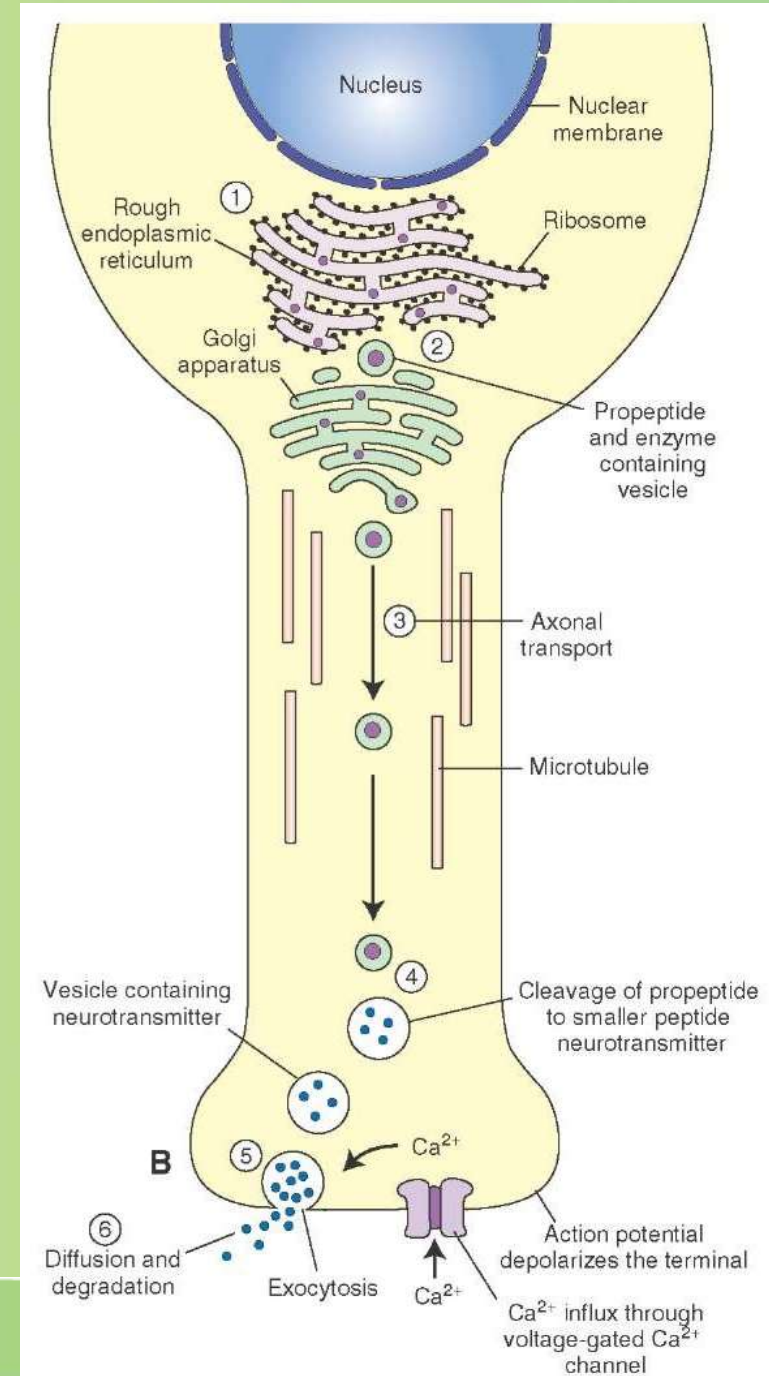
Processing of the pro-opiomelanocortin (*POMC*) precursor proceeds in an ordered, stepwise fashion. Some of the reactions are tissue specific. *ACTH*, adrenocorticotrophic hormone; *CLIP*, corticotropin-like intermediate lobe peptide; *JP*, joining peptide; *LPH*, lipotropin; *MSH*, melanocyte-stimulating hormone; *PC*, prohormone convertase.

The levels of regulation of neuropeptide expression

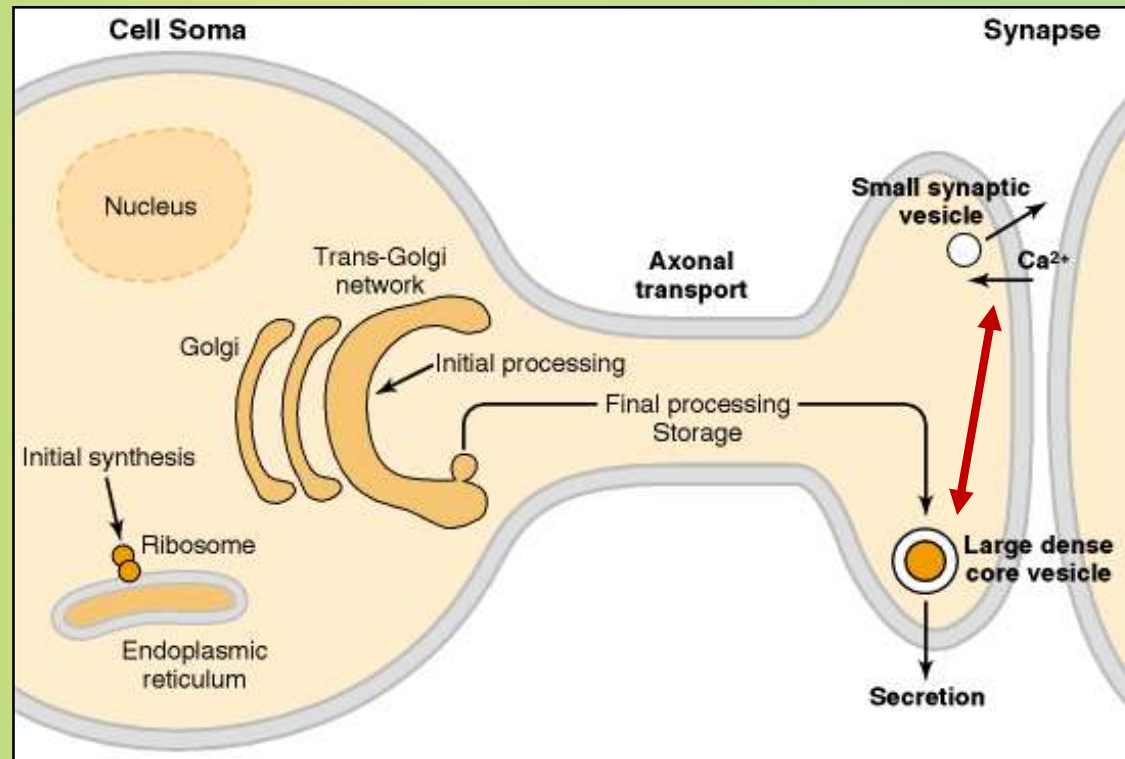


Stages of action

- Synthesized in ER (1) as pre-propeptides then propeptides, and then go into Golgi apparatus (2)
- Packaged into large-dense-core vesicles (with modifying enzymes)
- Transported via (3) fast-axonal transport
 - During the transport, proteases cleave the precursor neuropeptide into the final mature form (4).
- Released (5)
 - Release is gradual over time in response to general increases in the level of intracellular calcium.
- Action (prolonged)
 - Mainly via GPCR
- Termination by diffusion and degradation (6)



Role of Ca^{2+} ions



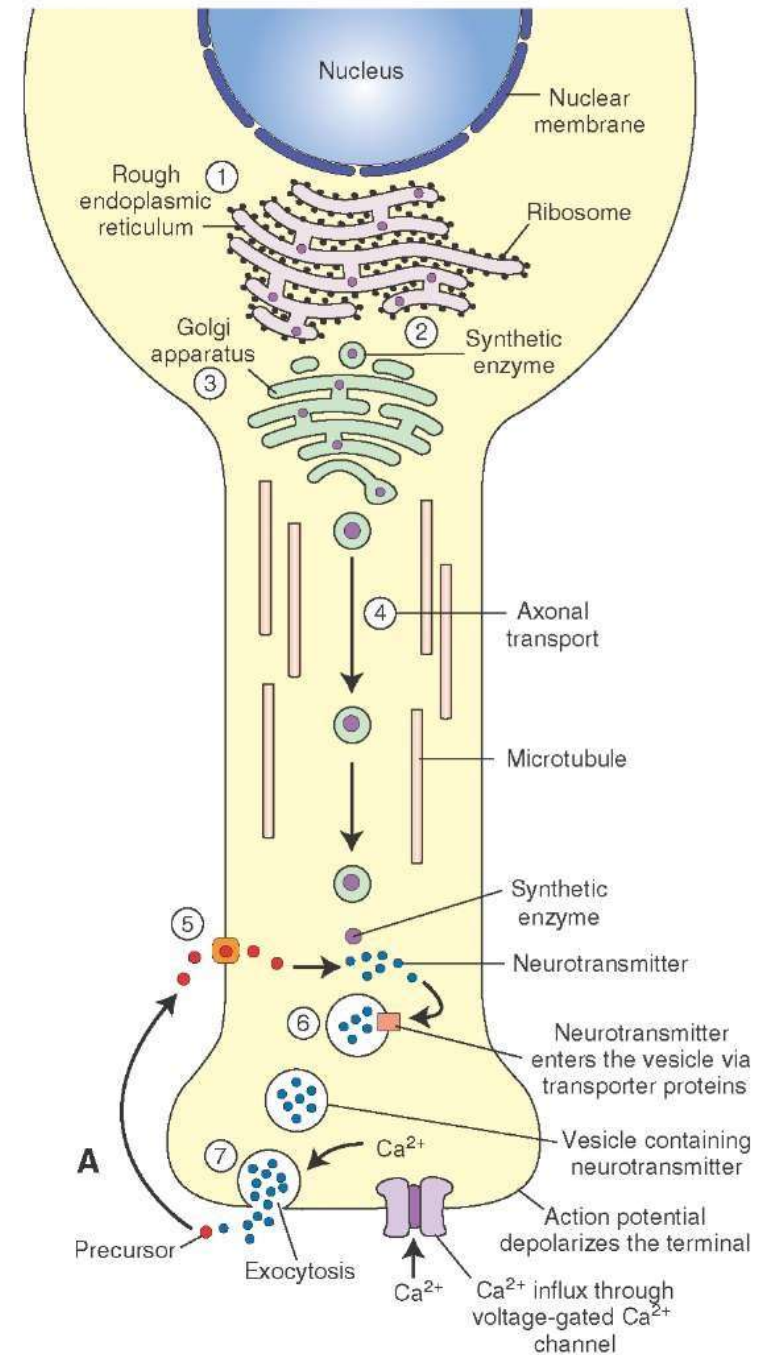
- Vesicles are located further away from the presynaptic membrane and away from the area of Ca^{2+} ions influx
- Ca^{2+} ion influx can be from external or internal sources and at higher concentrations than required for small-molecule neurotransmitters.

SMALL-MOLECULE NEUROTRANSMITTERS

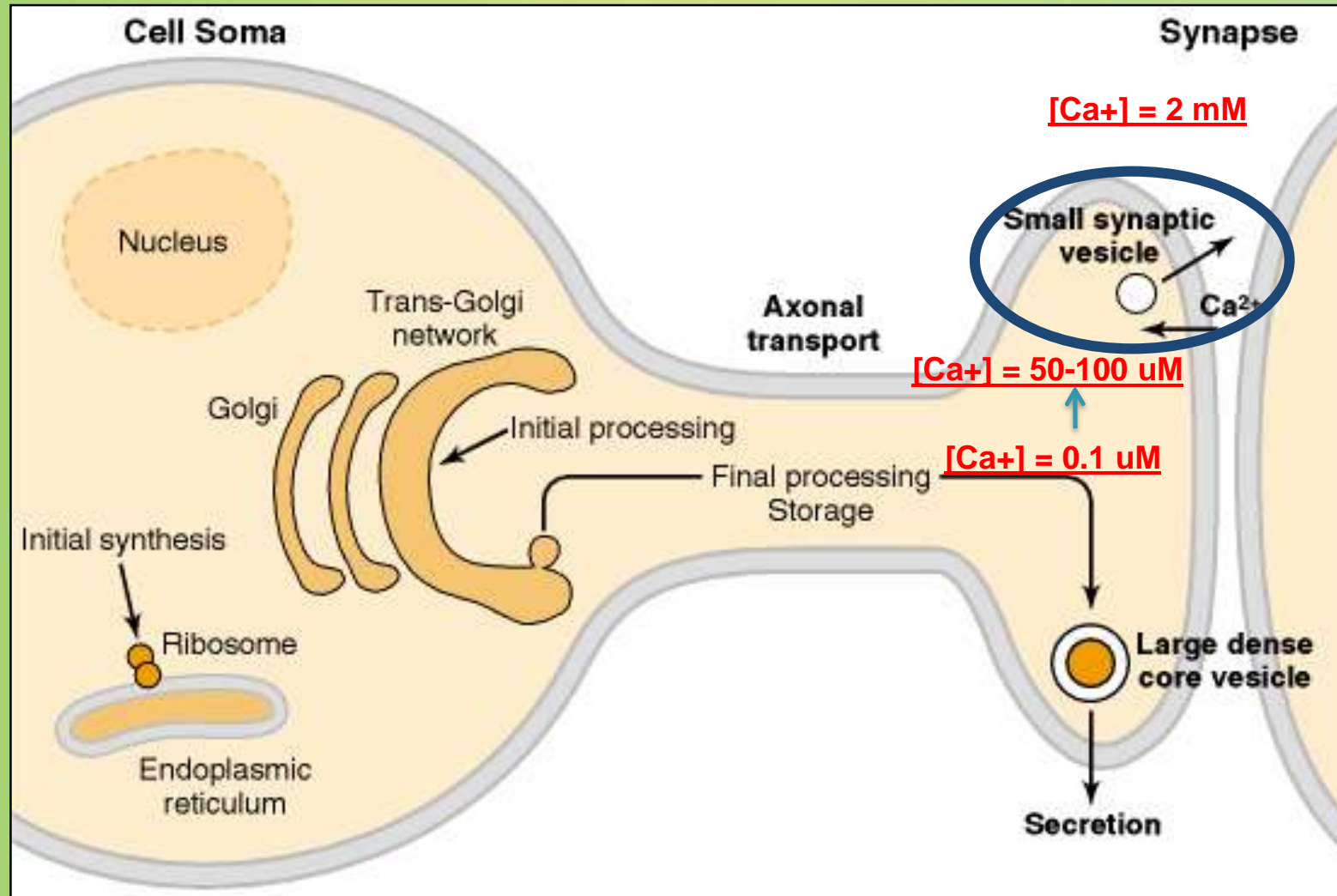


Stages of synthesis and action

- Synthesis of **the enzymes** in ER (1) and Golgi apparatus (2) where they are modified (3).
- Transport of **soluble** enzymes via slow axonal transport (4)
- Neurotransmitter precursors are taken up into the cells via transporter proteins located in the plasma membrane of the nerve terminal (5), and the neurotransmitter is synthesized in the presynaptic nerve terminal and then packaged in small synaptic vesicles (6).
- Release is stimulated by brief pulses each time an action potential triggers the influx of calcium.
- Action (short)
- Termination by diffusion, re-uptake, glial cell uptake, or inactivation



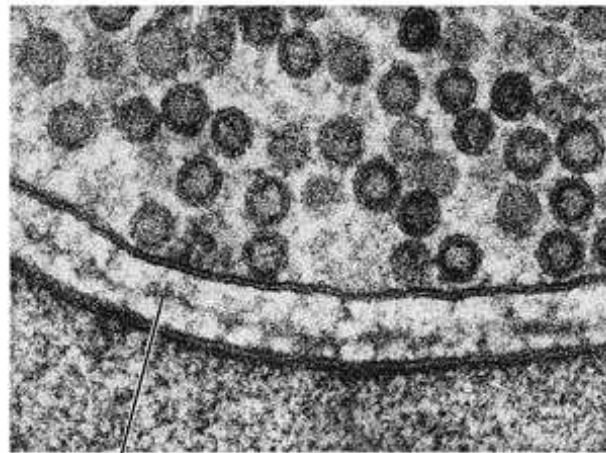
Role of Ca^{2+} ions



Vesicles are located near the presynaptic membrane and the area of Ca^{2+} ions influx.

Presynaptic membrane (thin section)

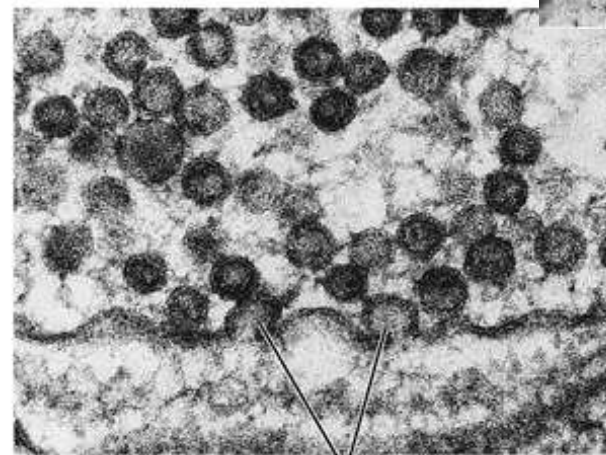
A₂



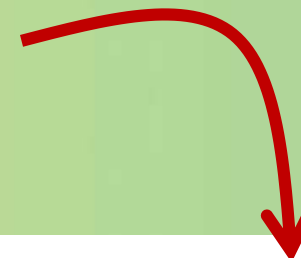
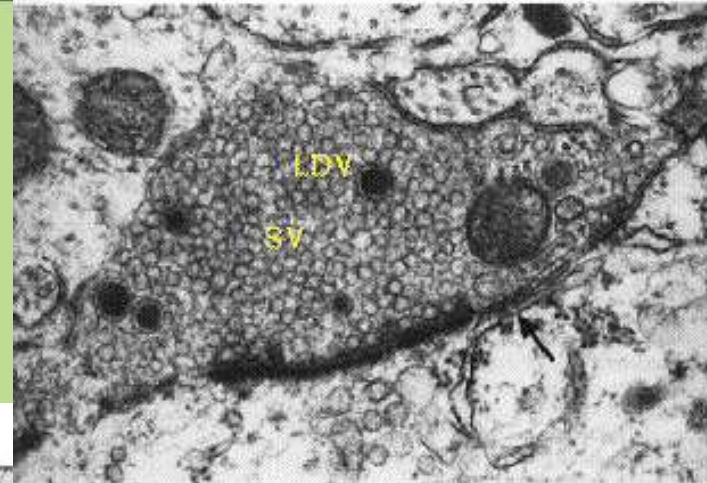
Synaptic cleft



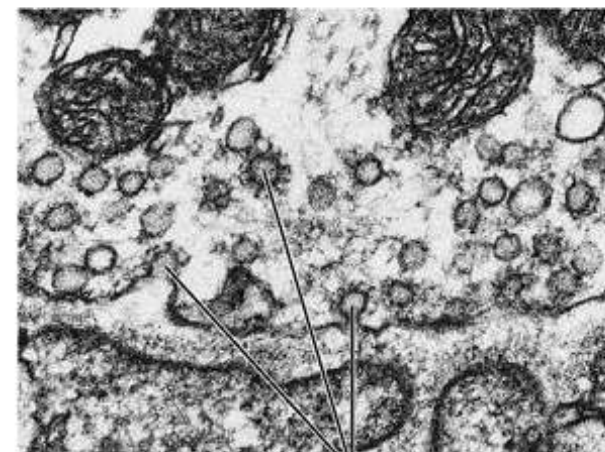
B₂



Vesicle fusions



C₂



Coated vesicles

The influx of Ca^{2+} ions allows the vesicles to fuse with the presynaptic membranes.

TYROSINE-DERIVED NEUROTRANSMITTERS

Dopamine, norepinephrine, and epinephrine

Notes

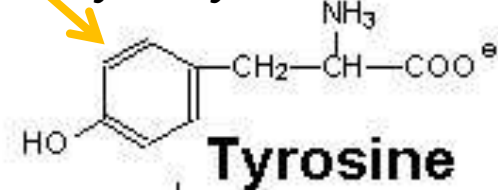


- Role of cofactors
 - S-adenosylmethionine (methyl transfer)
 - Pyridoxal phosphate (vitamin B6): transamination, decarboxylation
 - Tetrahydrobiopterin (BH4)

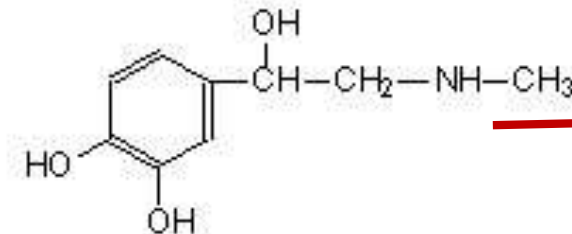


Diet/
liver

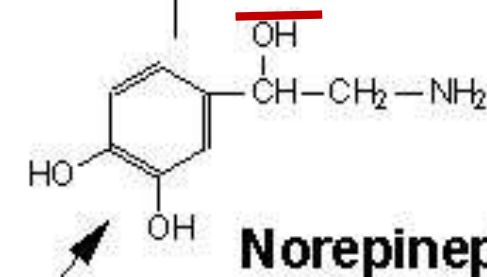
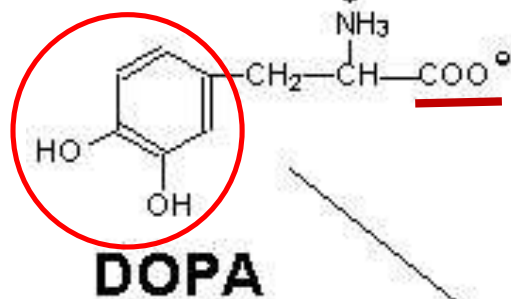
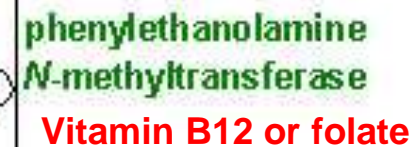
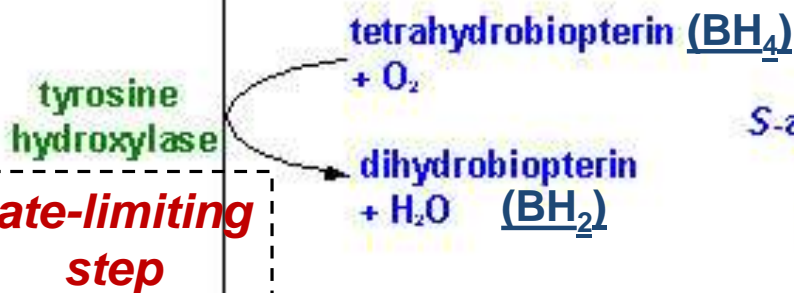
phenylalanine hydroxylase



Tyrosine (hydroxy-phenylalanine) is present in all food products and synthesized from phenylalanine. It enters the neuron by active transport.



Epinephrine



Norepinephrine

cytoplasm

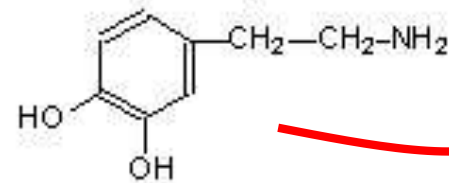
DOPA decarboxylase

Pyridoxal phosphate

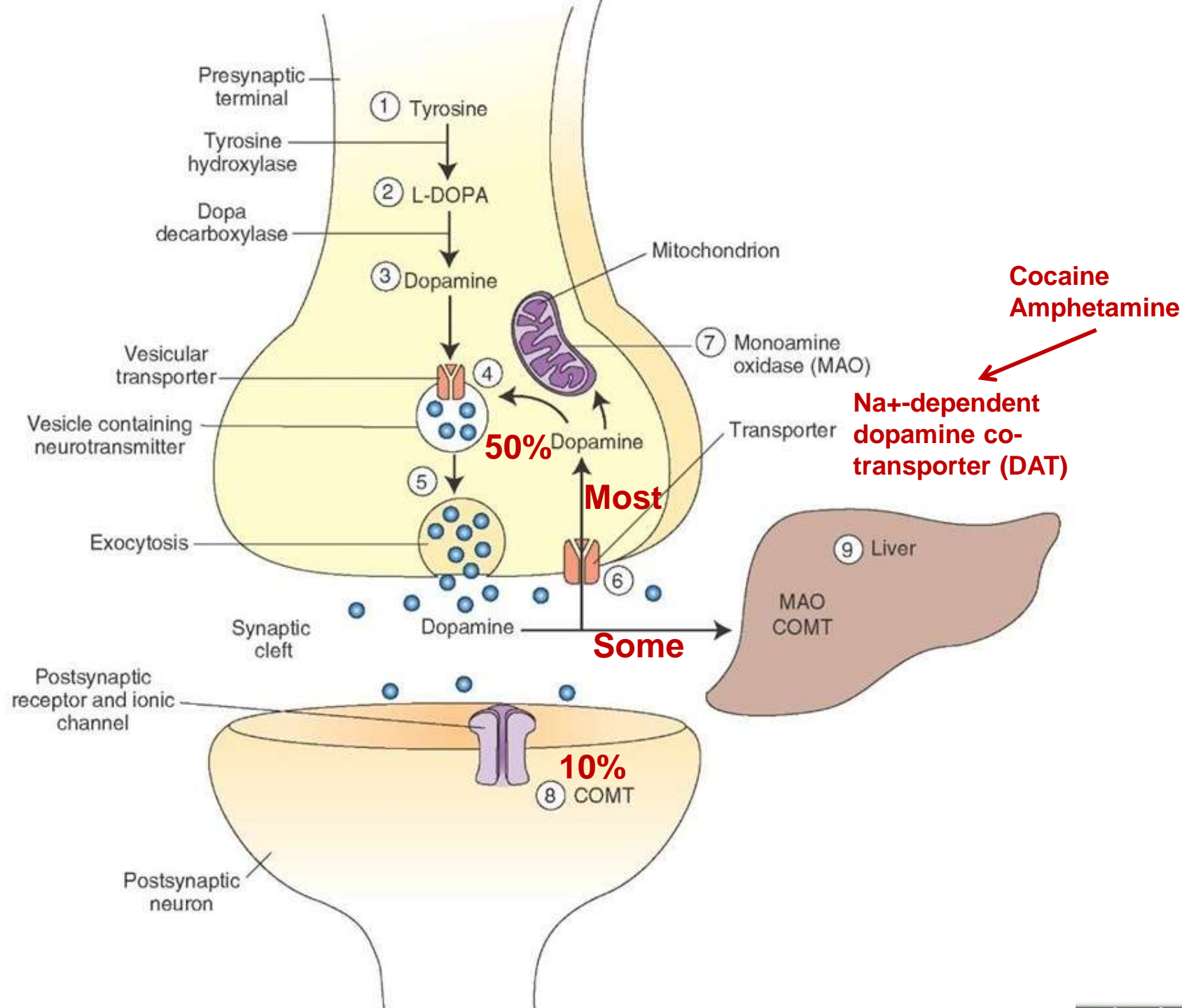
CO₂

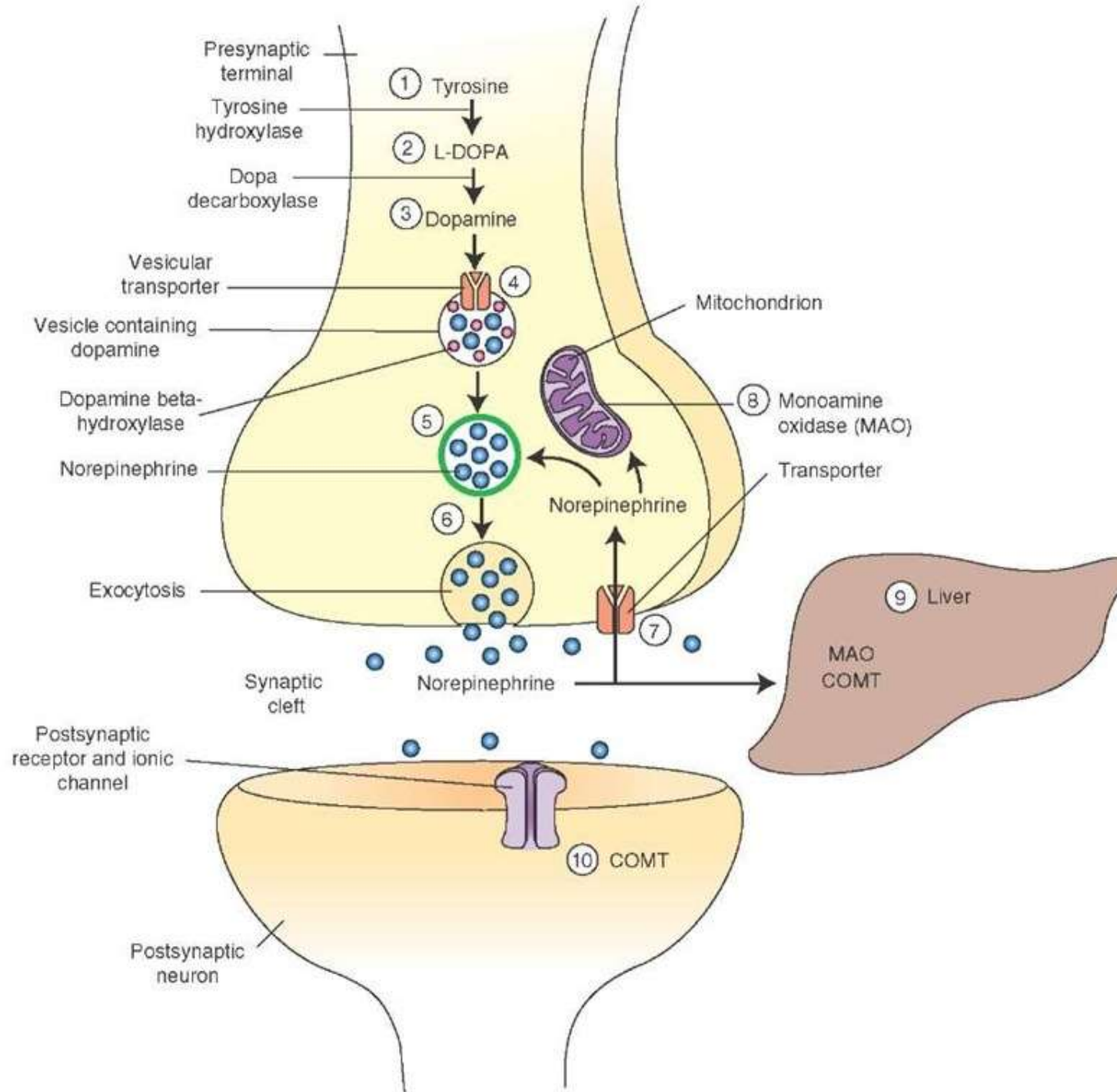


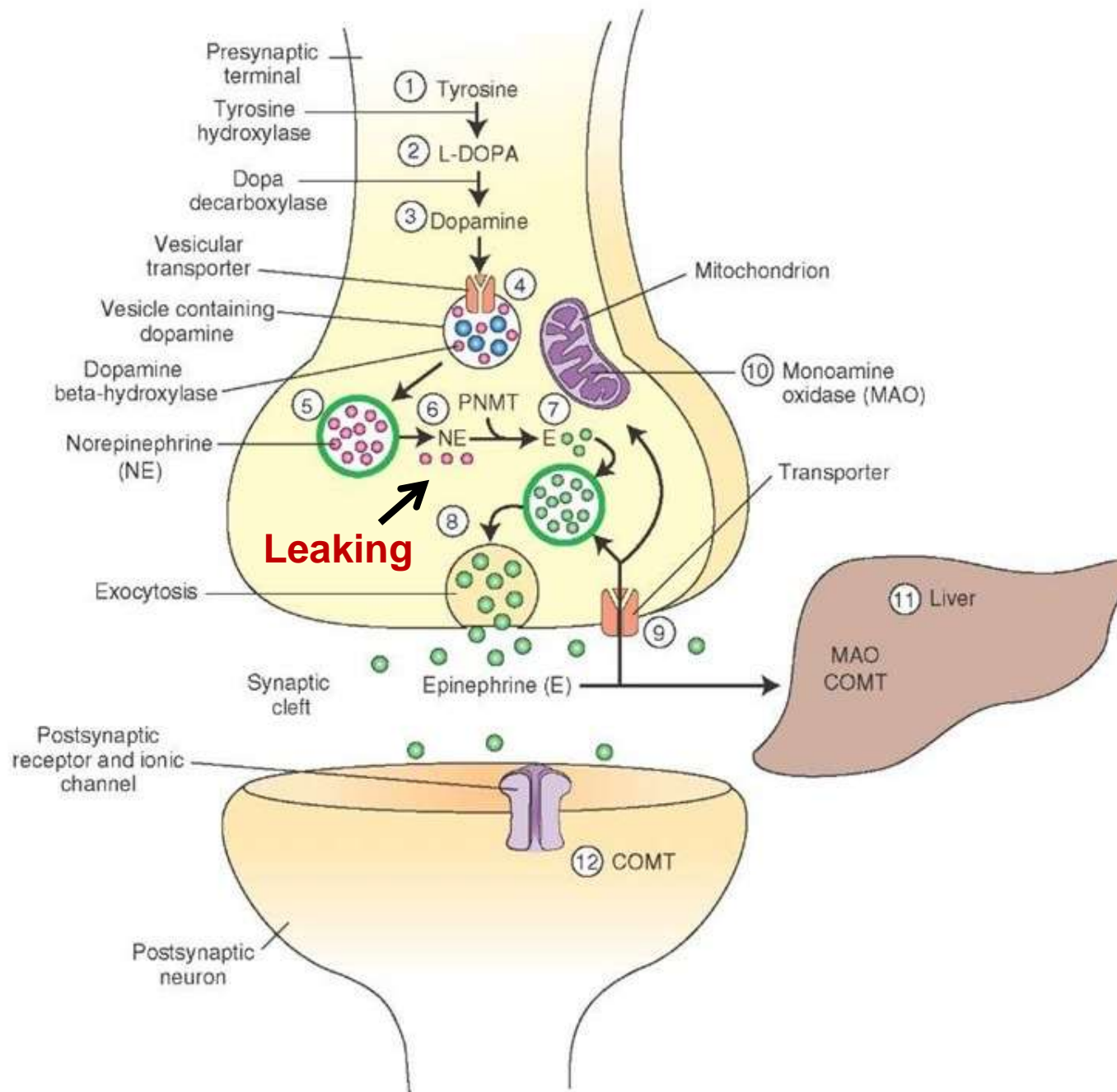
vesicular



Dopamine

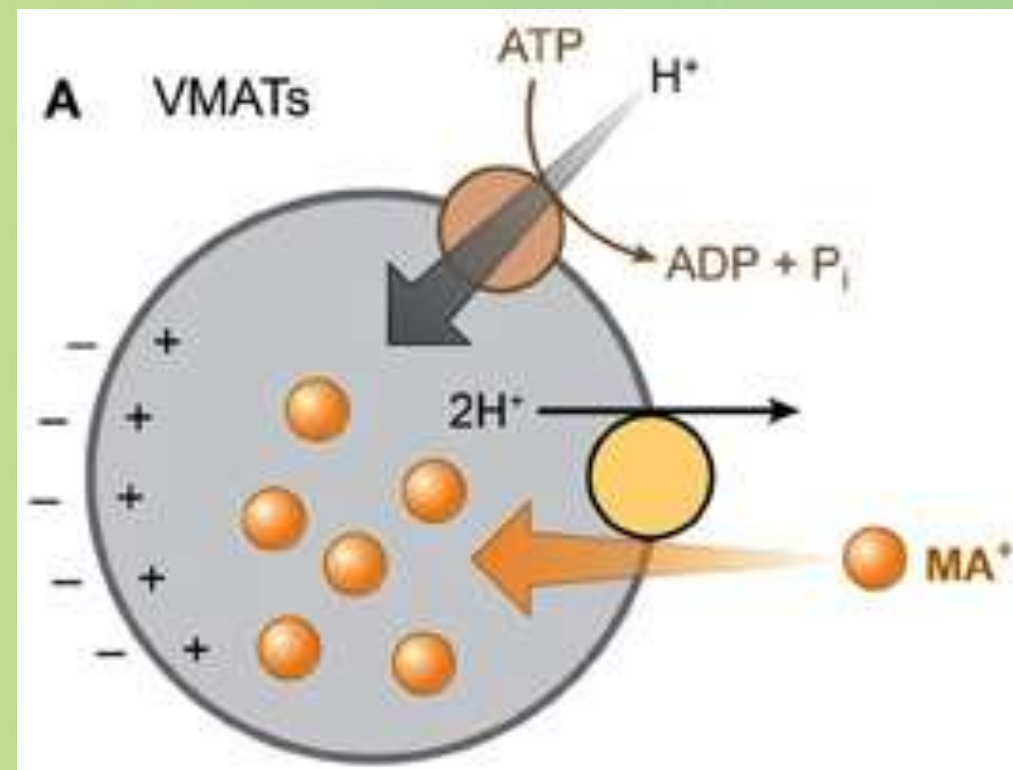




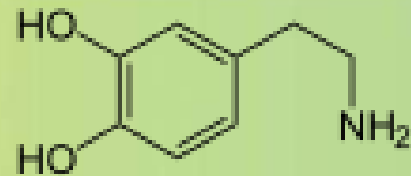


Packaging into vesicles

- The catecholamines (dopamine and epinephrine) are transported into vesicles by an ATP-dependent process linked to a proton pump.
- Protons are pumped into the vesicles by a vesicular ATPase (V-ATPase).
- The protons then exchange for the positively-charged catecholamine via the transporter VMAT (vesicular monoamine transporter).
- Targeting VMATs causes depletion of the neurotransmitters.

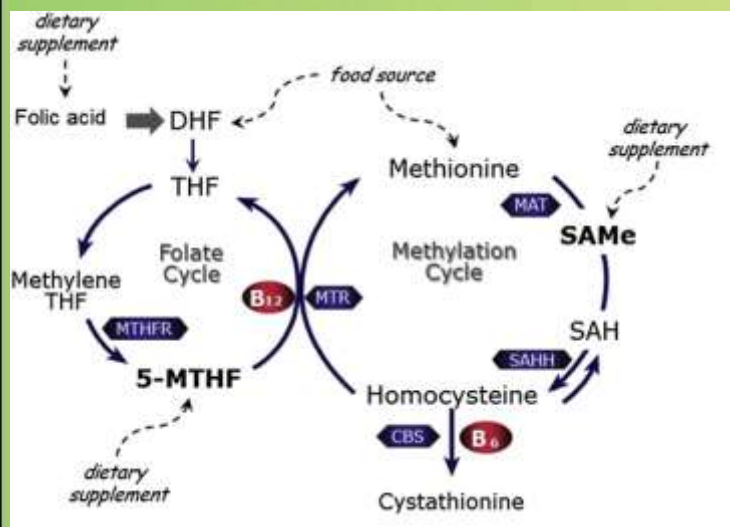


COMT and MAO



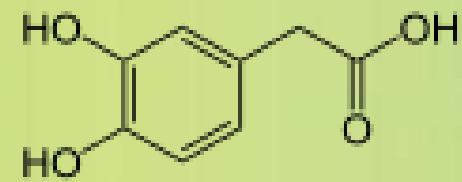
Dopamine (DA)

Degradative enzymes are present in the presynaptic terminal and in adjacent cells



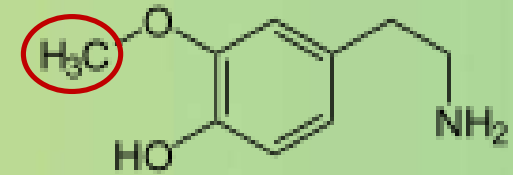
Inactivation is dependent on S-adenosylmethionine (SAM) and, indirectly, vitamin B12 and folate

Monoamine oxidase (MAO), Aldehyde dehydrogenase



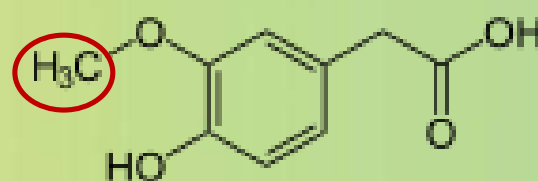
3,4-Dihydroxyphenylacetic acid (DOPAC)

Catechol-O-methyltransferase (COMT)



3-Methoxytyramine (3-MT)

Catechol-O-methyltransferase (COMT)



Homovanillic acid (HVA)

Monoamine oxidase (MAO), Aldehyde dehydrogenase

Drugs that deplete storage vesicles indirectly increase catecholamine degradation.



Regulation

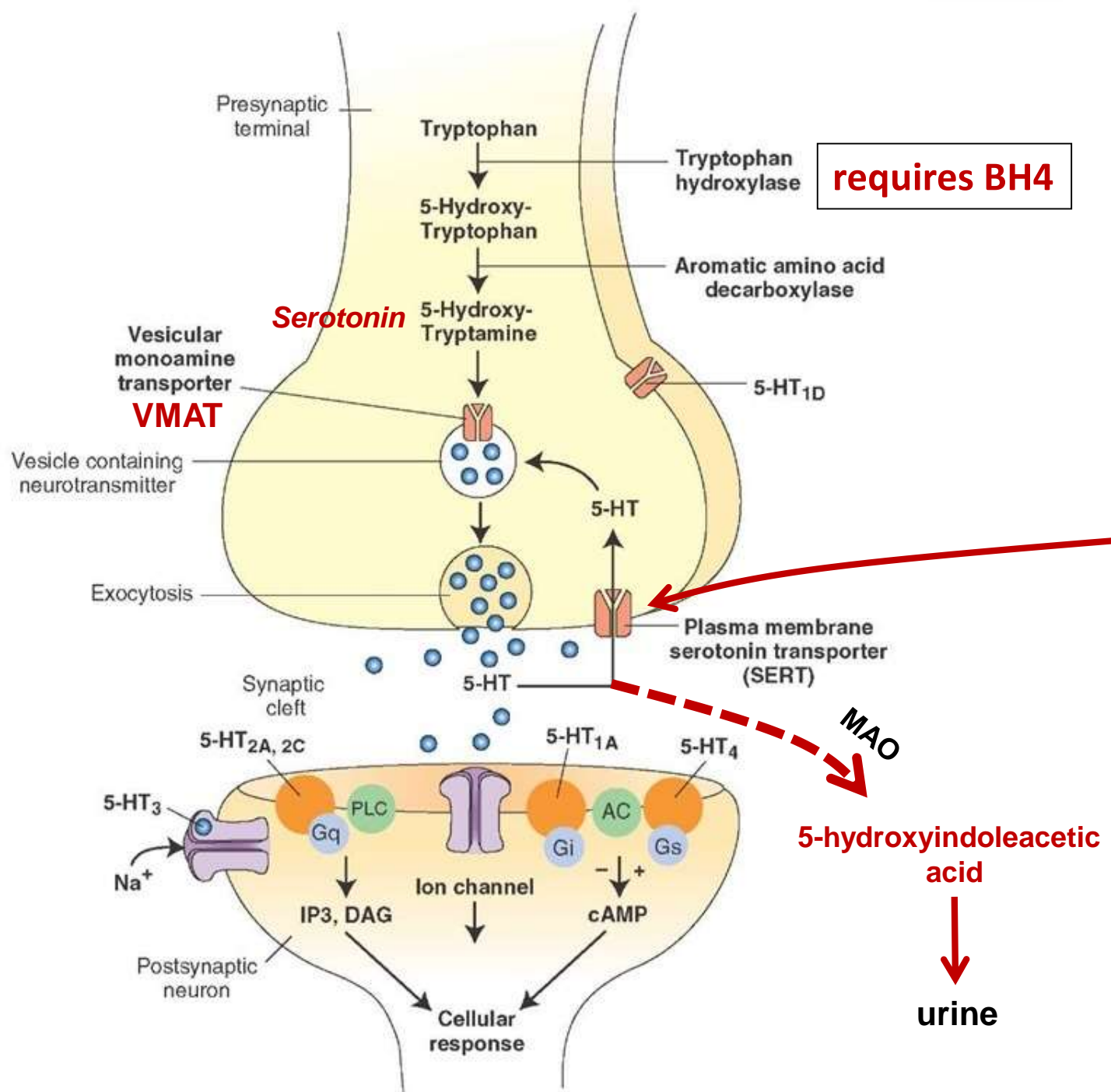


- Tyrosine hydroxylase
 - Short-term:
 - Inhibition by free cytosolic catecholamines, which compete with BH₄ binding to the enzyme.
 - Activation by depolarization, which activates several protein kinases including PKC, PKA, Ca²⁺-calmodulin-dependent kinases that phosphorylate tyrosine hydroxylase. This makes the enzyme bind more tightly to BH₄ and, consequently, less sensitive to end-product inhibition.
 - Long-term (plus dopamine β-hydroxylase)
 - Prolonged sympathetic neuronal activity increases the amounts of tyrosine hydroxylase and dopamine β-hydroxylase mRNAs.

TRYPTOPHAN-DERIVED NEUROTRANSMITTERS

Serotonin and melatonin





requires BH4

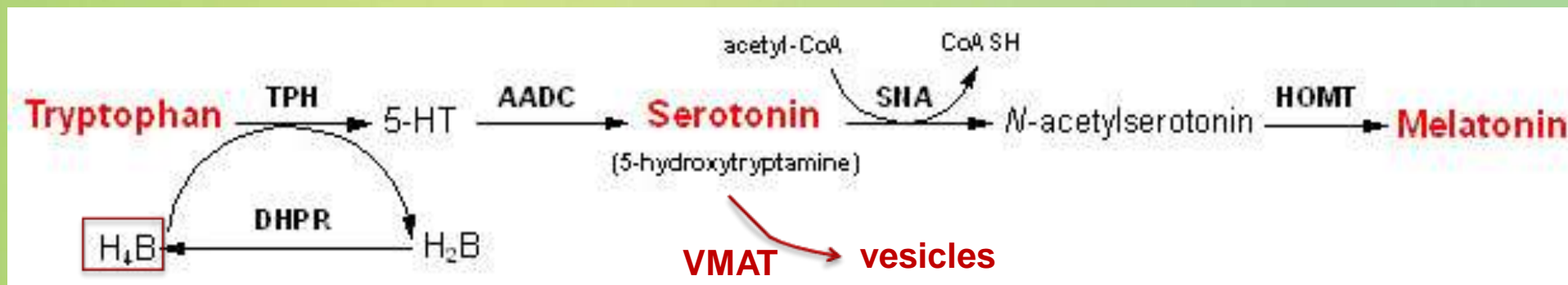
Antidepressants, called selective serotonin reuptake inhibitors (SSRIs) like Prozac® inhibit the reuptake process resulting in prolonged serotonin presence in the synaptic cleft.

Serotonin is packaged into vesicles by VMAT.

5-hydroxyindoleacetic acid
↓
urine

Melatonin

- Serotonin is synthesized in the pineal gland and serves as a precursor for the synthesis of melatonin, which is a neurohormone involved in regulating:
 - sleep patterns
 - seasonal and circadian (daily) rhythms
 - dark-light cycle

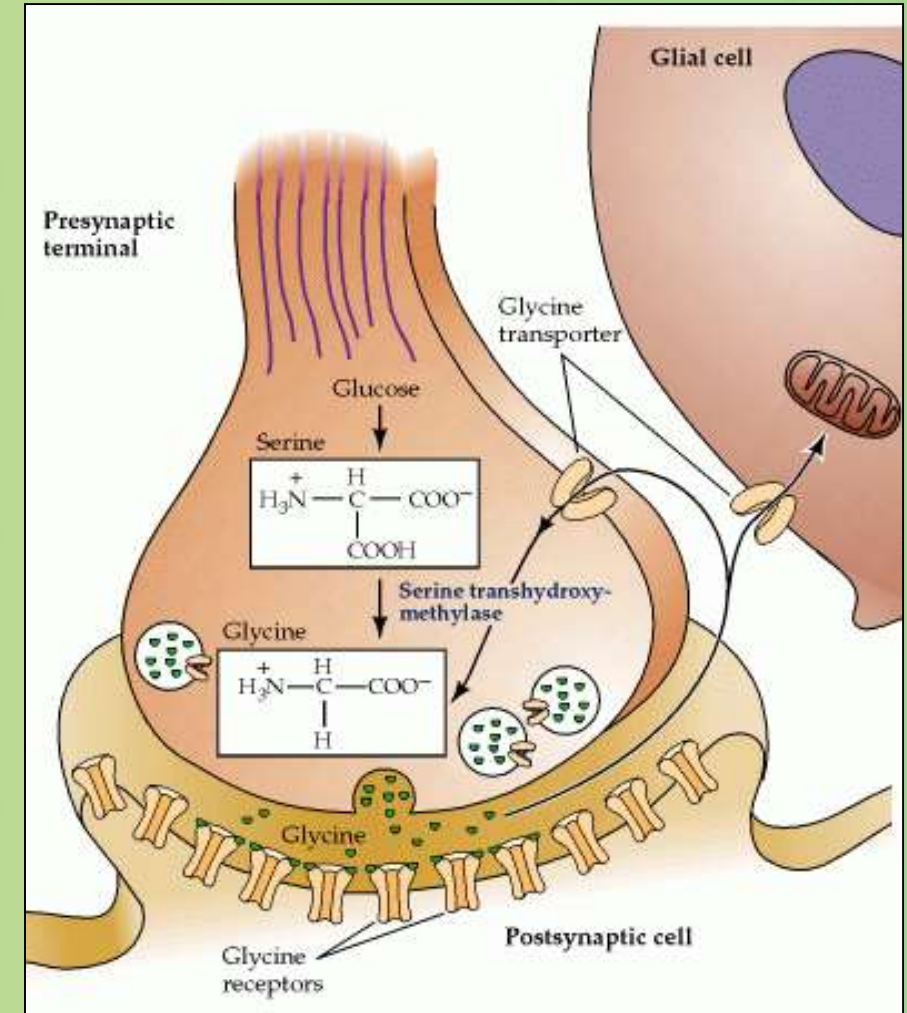
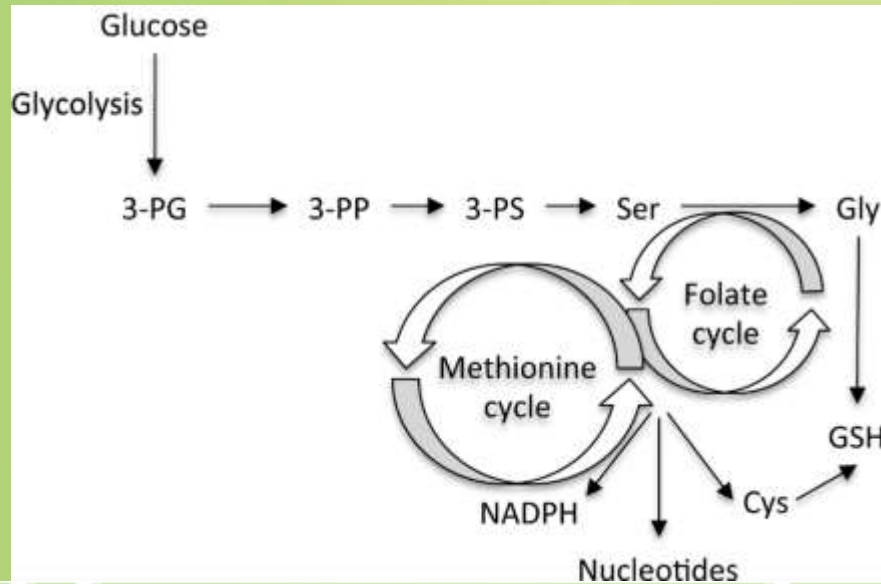


AMINO ACID-BASED NEUROTRANSMITTERS



Glycine

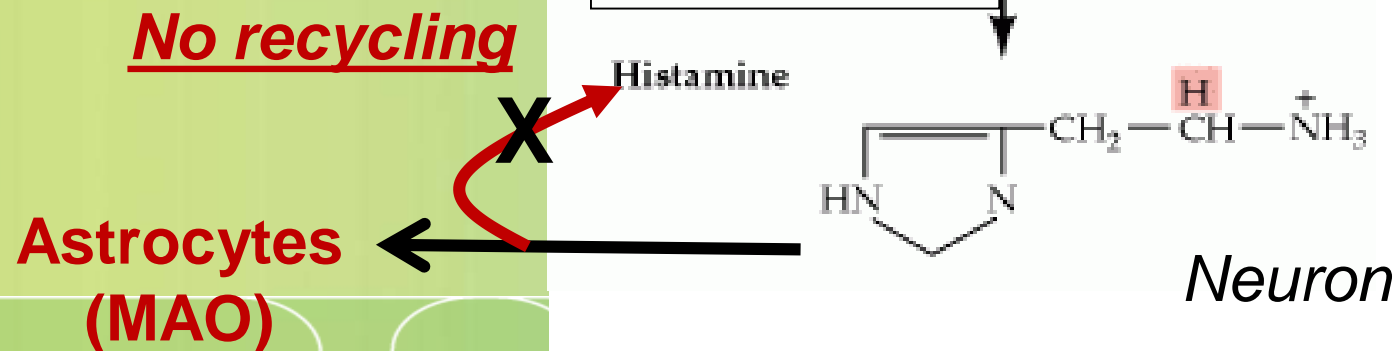
- A major inhibitory neurotransmitter
- It is synthesized from serine by serine hydroxymethyltransferase through 3-phosphoglycerate.
- Removal: high-affinity transporter



Histamine

- It does not penetrate the blood-brain barrier and, hence, must be synthesized in the brain.
- Histamine is inactivated by two enzymes—histamine methyltransferase and diamine oxidase (histaminase).

Histamine is packaged into vesicles by VMAT.





Glutamate and aspartate

- Nonessential amino acids
- Do not cross BBB
 - must be synthesized in neurons
- Main synthetic compartments
 - neurons
 - glial cells
- Both are excitatory neurotransmitters.

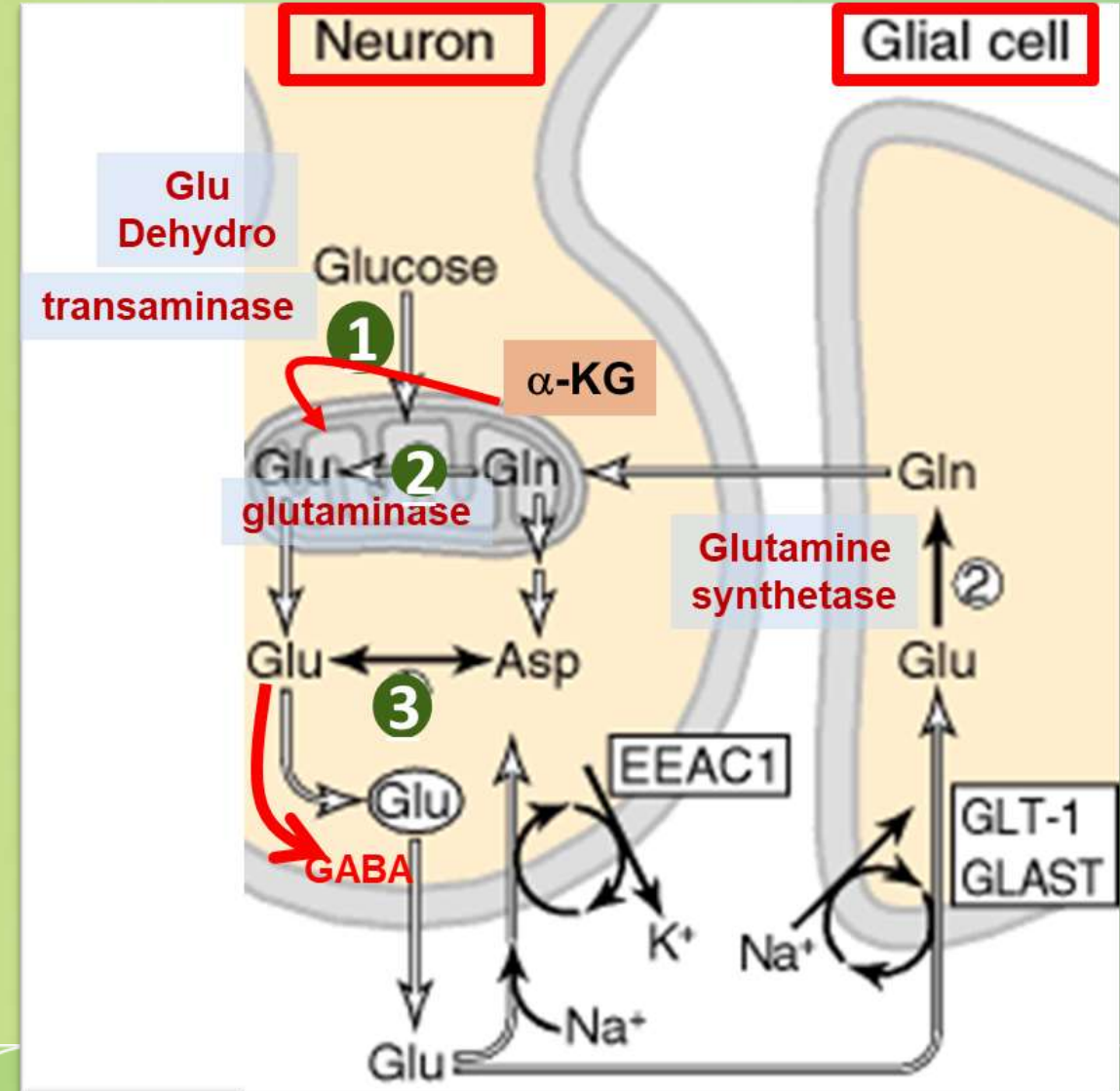
Synthesis of glutamate

Sources:

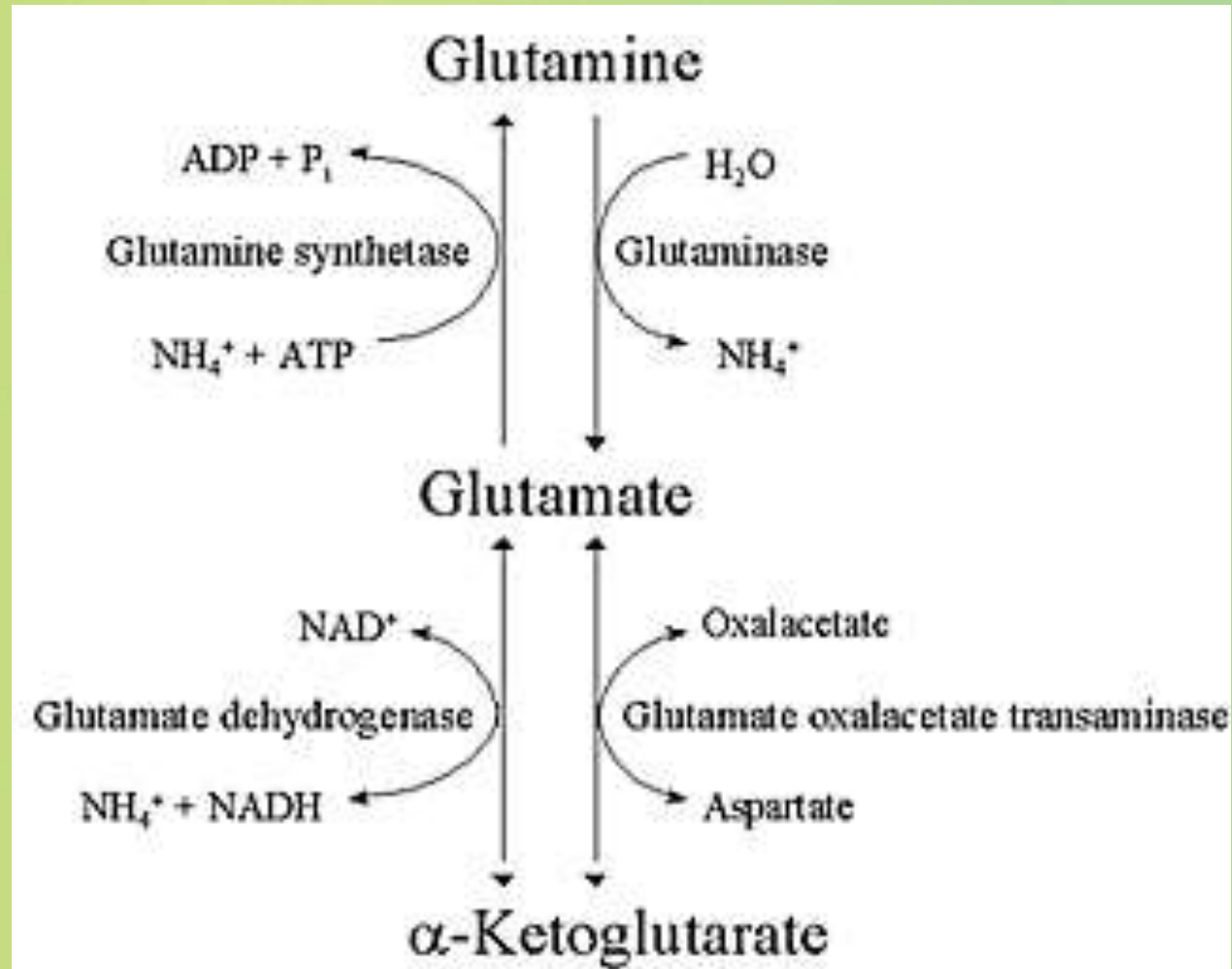
1. Glycolysis → Krebs cycle → dehydrogenation of α -ketoglutarate
2. Glutamine (deamination)
3. Aspartate (transamination)

Removal

- Reuptake: Excitatory amino acid carrier-1 (EAAC1)
- Glial cells: Glutamate transporter-1 (GLT-1) and glutamate—aspartate transporter (GLAST)



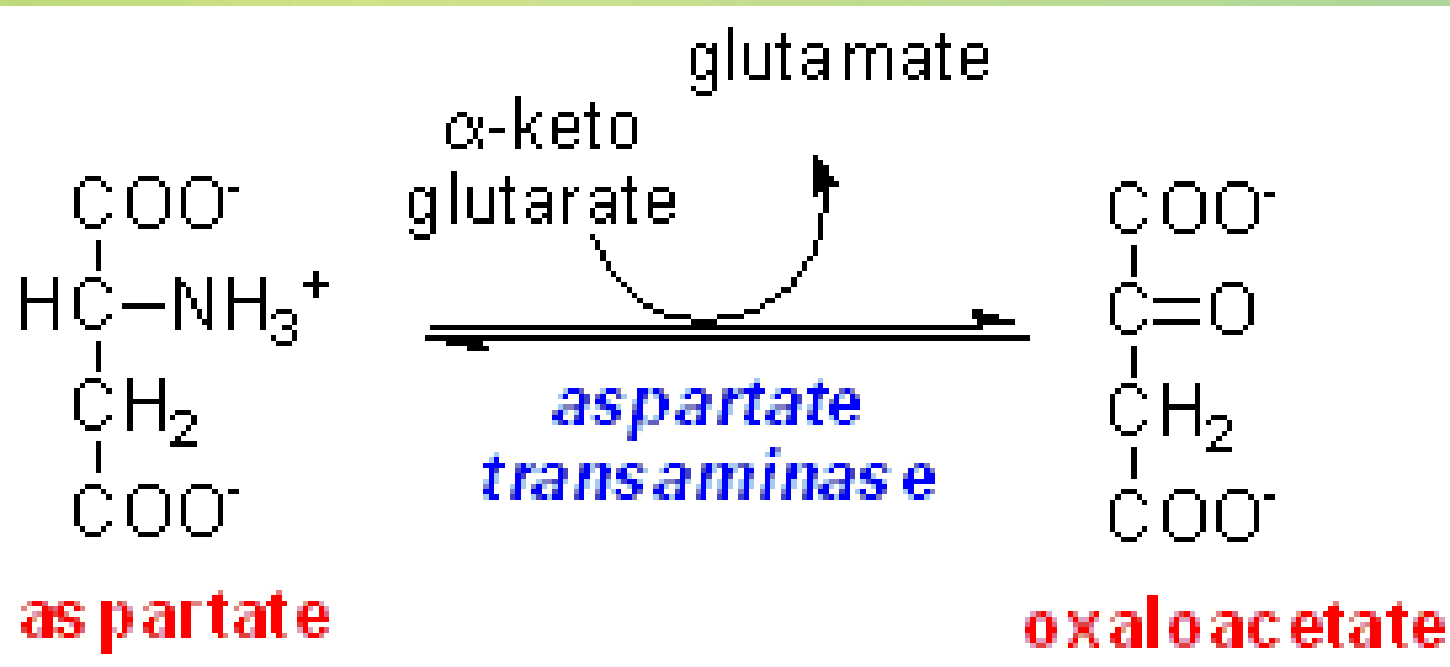
Sources of glutamate (*supplementary*)





Aspartate

- Note: A vesicular uptake mechanism for aspartate has not yet been demonstrated, somewhat weakening the case for considering aspartate to be a neurotransmitter
- Precursor: oxaloacetate (transamination)



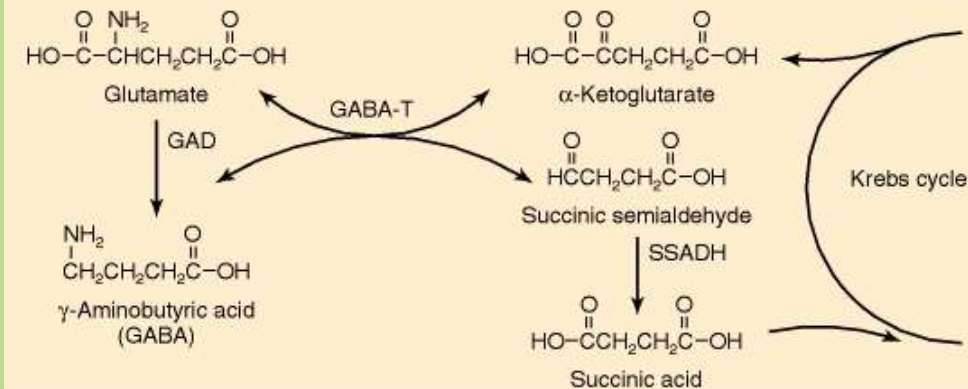
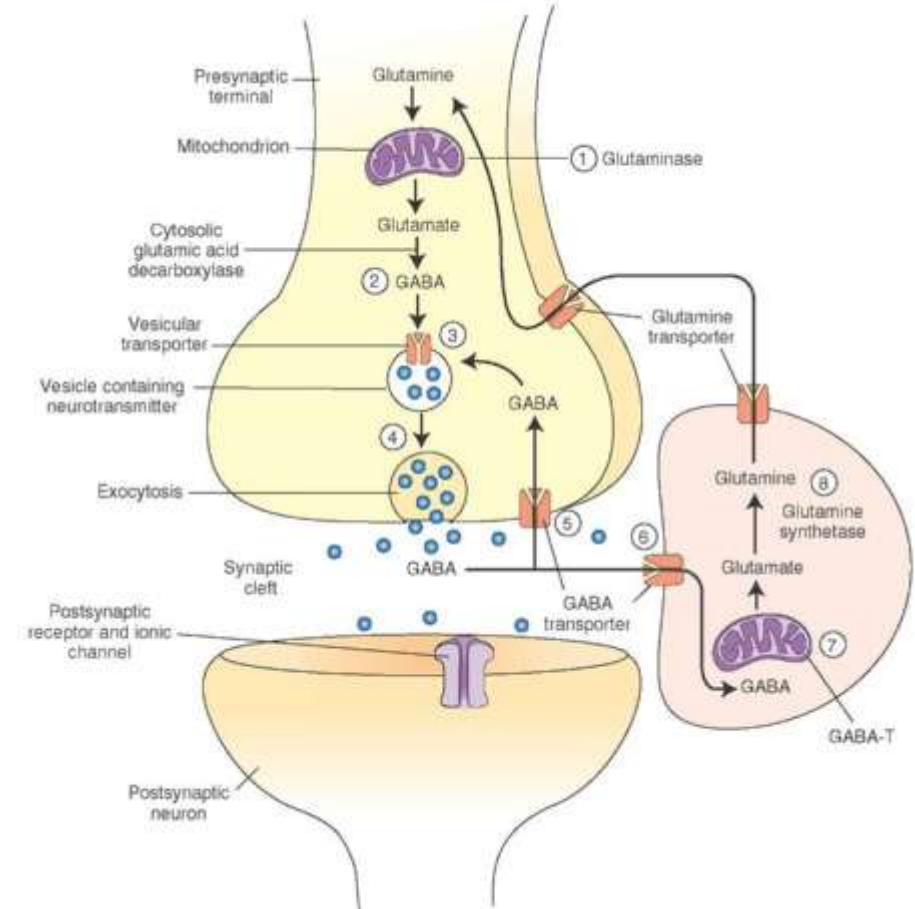


Gamma- aminobutyric acid (GABA)

- GABA is present in high concentrations (millimolar) in many brain regions.
 - These concentrations are about 1,000 times higher than concentrations of the classical monoamine neurotransmitters in the same regions.
- The GABA shunt is a closed-loop process with the dual purpose of producing and conserving the supply of GABA.

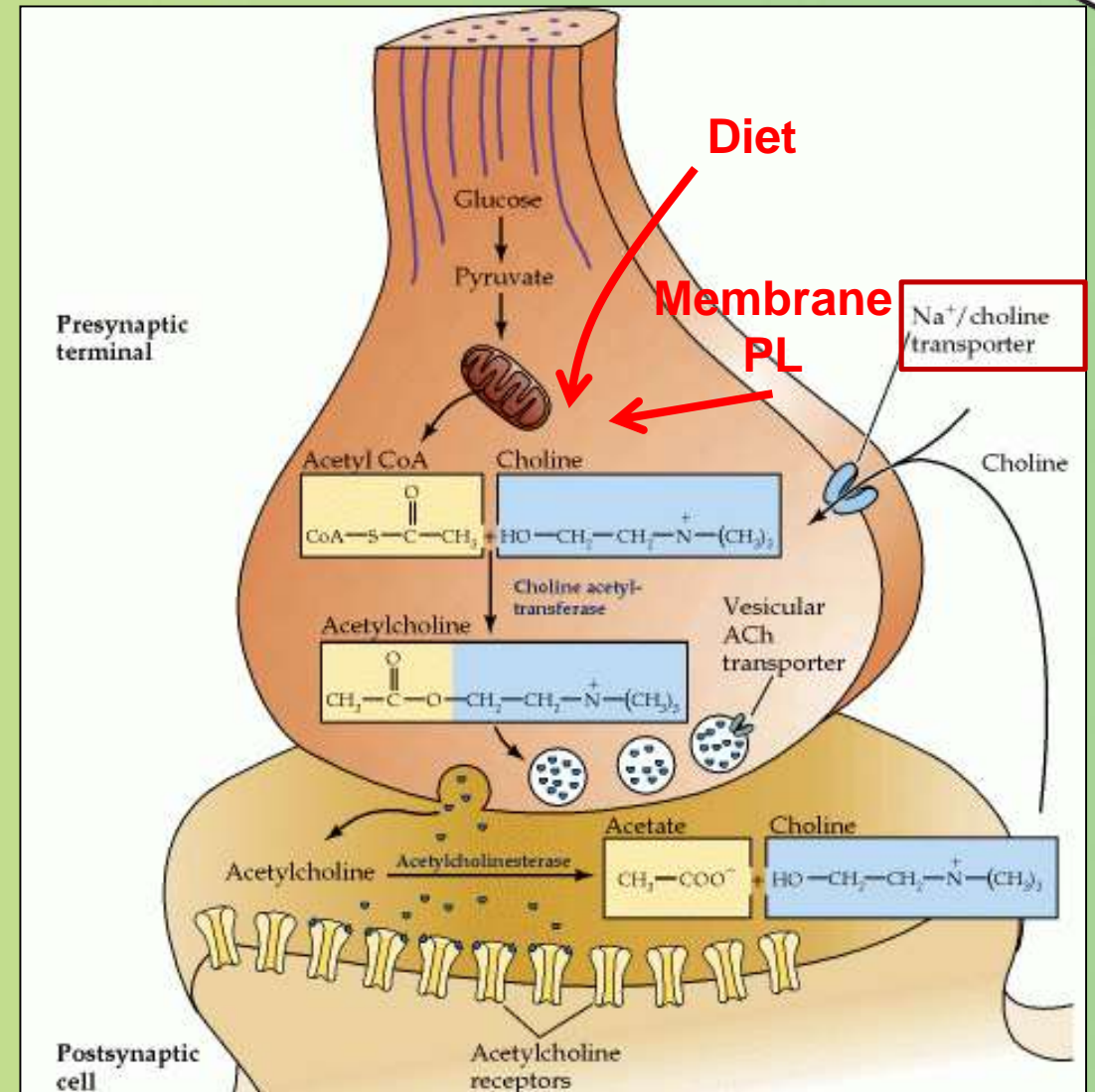
GABA shunt

- Gln → Glu by glutaminase.
- Glu → GABA by glutamate decarboxylase (GAD), which requires pyridoxal phosphate (vitamin B6).
- GABA is stored in vesicles until released.
- GABA is either
 - taken up into the presynaptic terminal and repackaged
 - goes into the GABA Shunt where it is taken up into the glia and converted to Glu.
 - Glu is converted into Gln, which is transported into the neighboring nerve terminals to synthesize Glu.



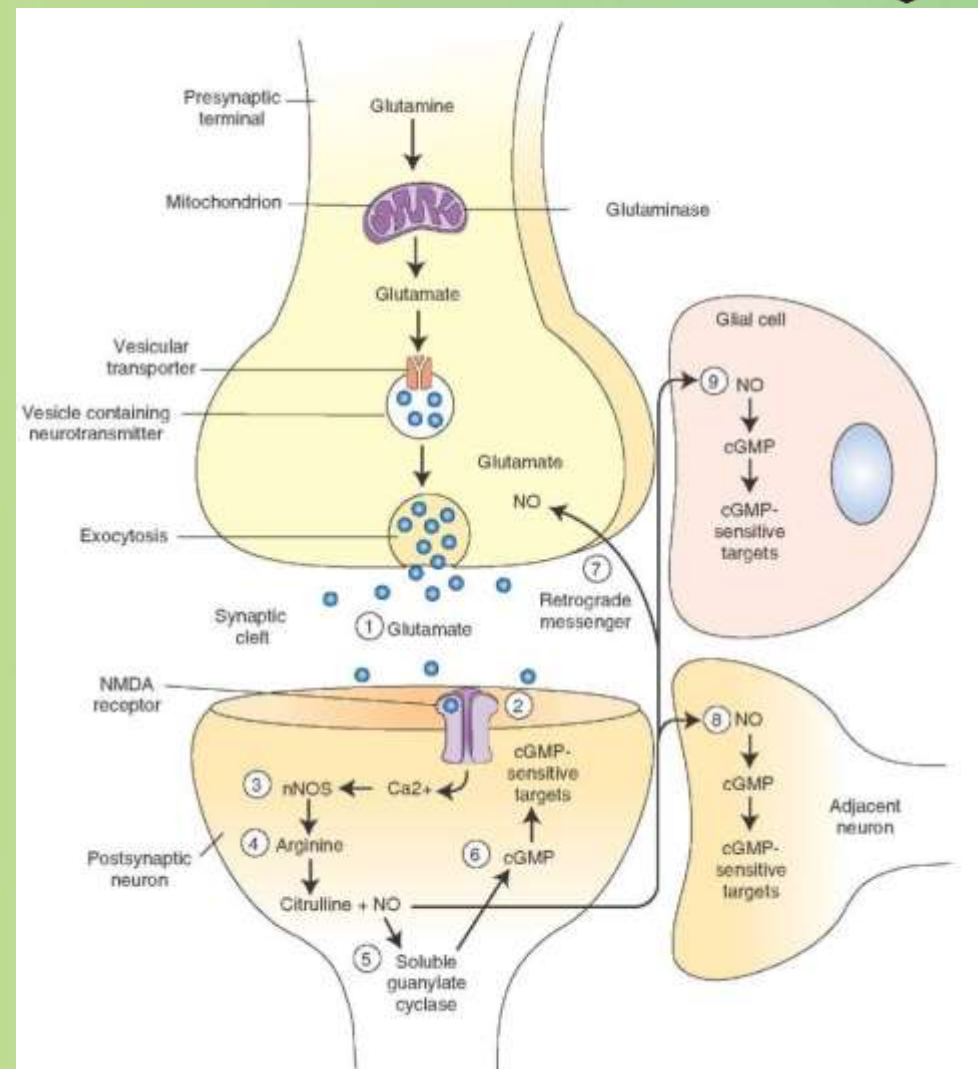
Synthesis of acetylcholine

- Choline + acetyl coenzyme-A by choline acetyltransferase in the cytoplasm.
- Transported into and stored in vesicles.
- Removal: hydrolysis by acetylcholinesterase



Nitric oxide (NO)

- Glutamate is released (1) and acts on The N-methyl-D-aspartate (NMDA) receptors located on the post-synaptic neuron (2)
- Ca^{2+} enters the postsynaptic neuron activating nitric oxide synthase (NOS) (3), which forms NO from arginine (4).
- NO stimulates guanylate cyclase forming cGMP (5), which results in a physiological response (6)
- NO can diffuse out:
 - a) to the presynaptic terminal (retrograde messenger) (7) prolonging effect and
 - b) into adjacent neurons (8) and glial cells (9) stimulating guanylate cyclase.
- It has a half-life of 2-4 seconds.
- NO is inhibited by hemoglobin and other heme proteins which bind it tightly.



Is NO a neurotransmitter?



- Yes, but:
 - It is not stored in vesicles
 - It is not released by calcium-dependent exocytosis (it diffuses)
 - Its inactivation is passive (there is no active process that terminates its action)
 - **It decays spontaneously**
 - It does not interact with receptors on target cells
 - **Its sphere of action depends on the extent to which it diffuses, and its action is not confined to the conventional presynaptic-postsynaptic direction.**
 - NO acts as a retrograde messenger and regulates the function of axon terminals presynaptic to the neuron in which it is synthesized.



NO synthase

- Isoform I (nNOS or cNOS)
 - **Neurons** and epithelial cells
 - activated by the influx of extracellular calcium
- isoform II (iNOS)
 - Macrophages and smooth muscle cells
 - induced by cytokines
- and isoform III (eNOS)
 - Endothelial cells lining blood vessels
 - activated by the influx of extracellular calcium
- All three isoforms require BH2 as a cofactor and nicotinamide adenine dinucleotide phosphate (NADPH) as a coenzyme.

