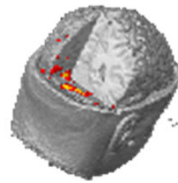


**Ce cours est enregistré
et mis en ligne sur les
plateformes UNIGE.**



**UNIVERSITÉ
DE GENÈVE**

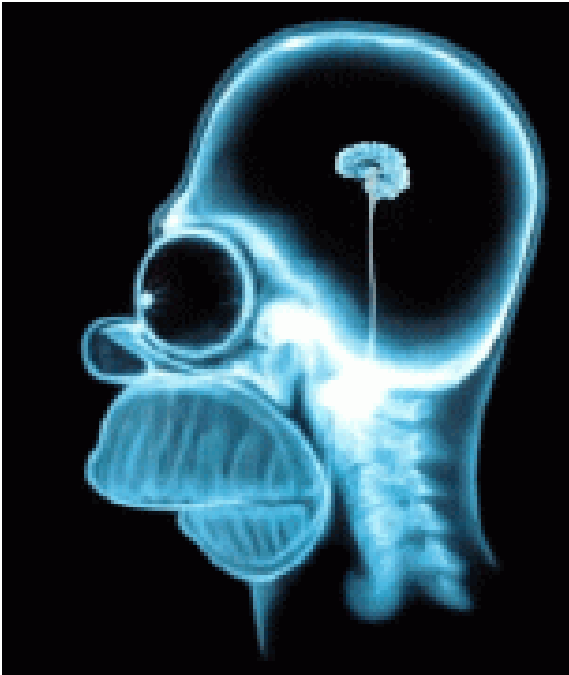
Neuro-anatomie & neuro-imagerie fonctionnelle



UNIVERSITÉ DE GENÈVE

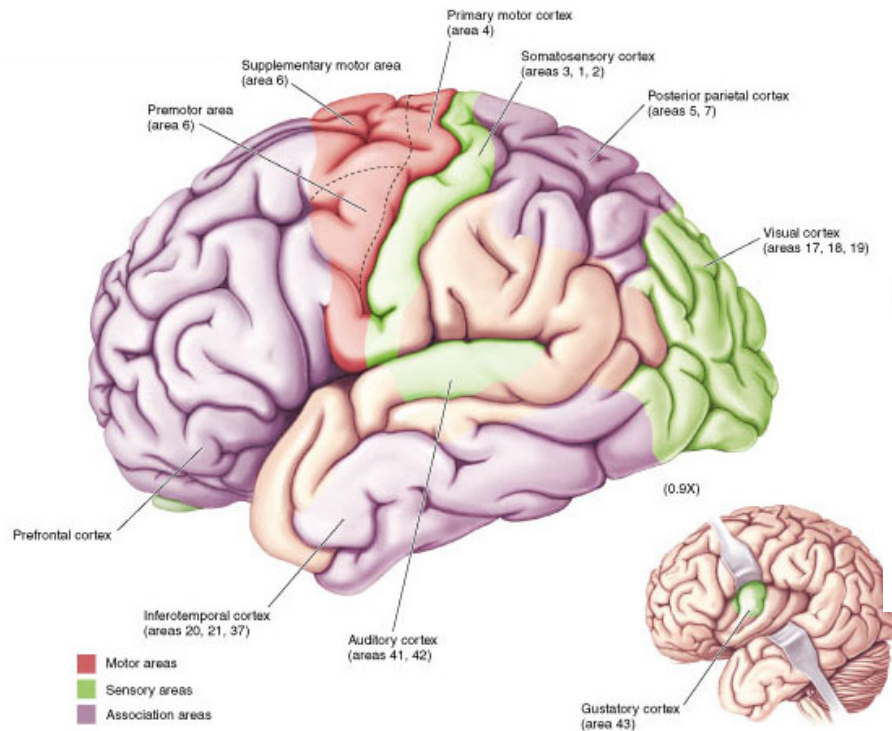
patrik.vuilleumier@unige.ch

Objectifs du cours

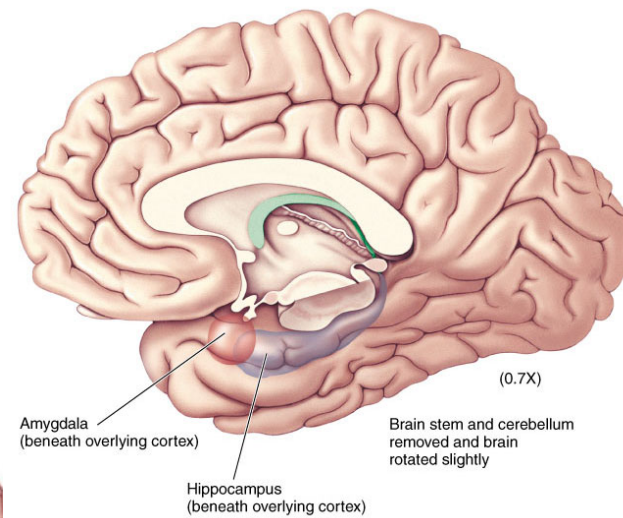


- anatomie macroscopique du cerveau:
 - organisation du cortex et connections
- techniques de neuroimagerie:
 - différentes techniques disponibles
 - origine du signal
 - possibilités & limites
- NB: sujets humains

Brefs rappels de Neuro Anatomie

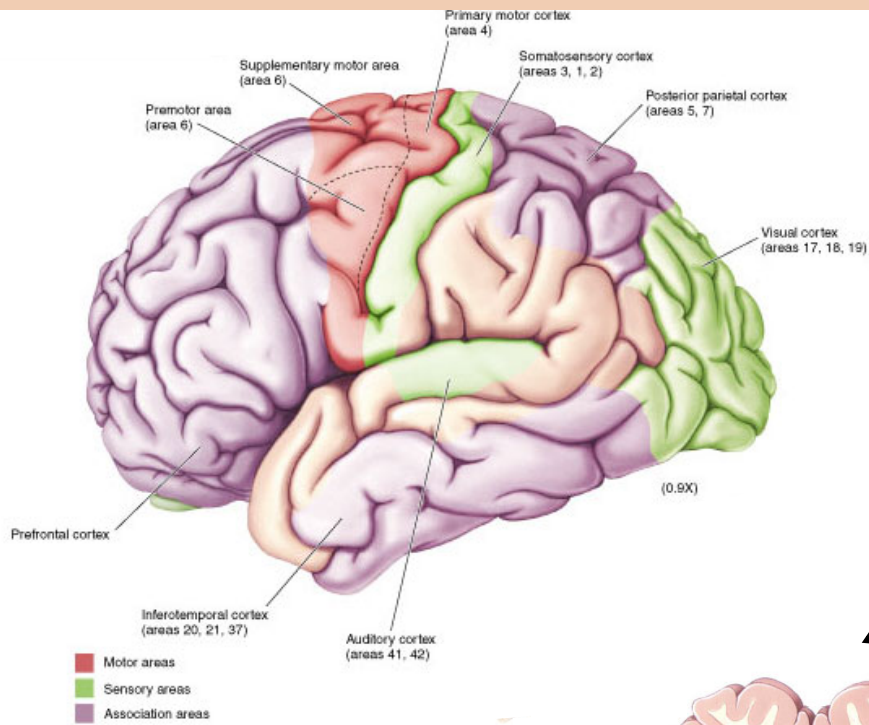


Surface latérale

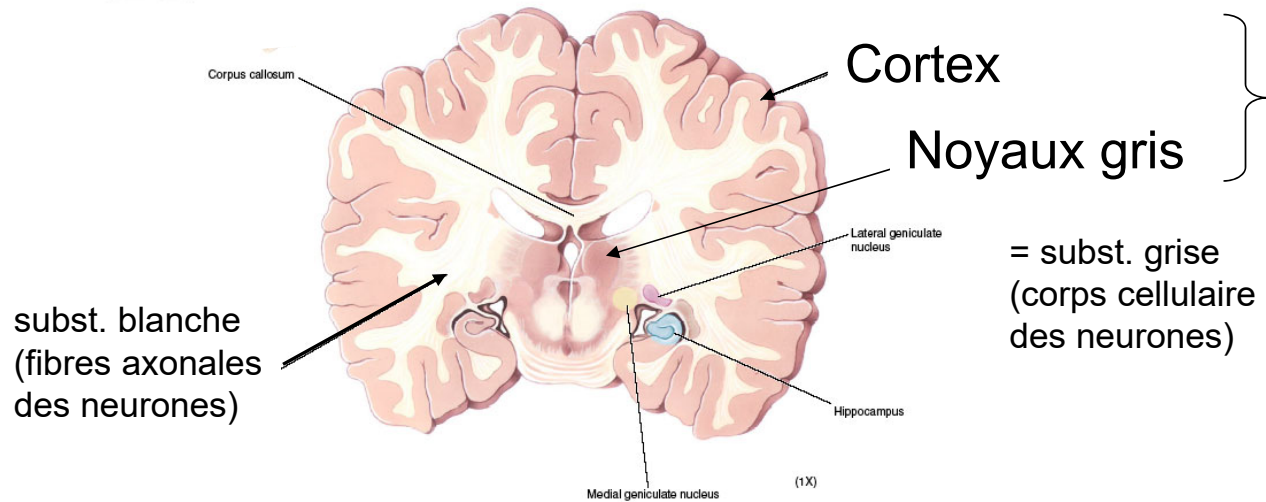
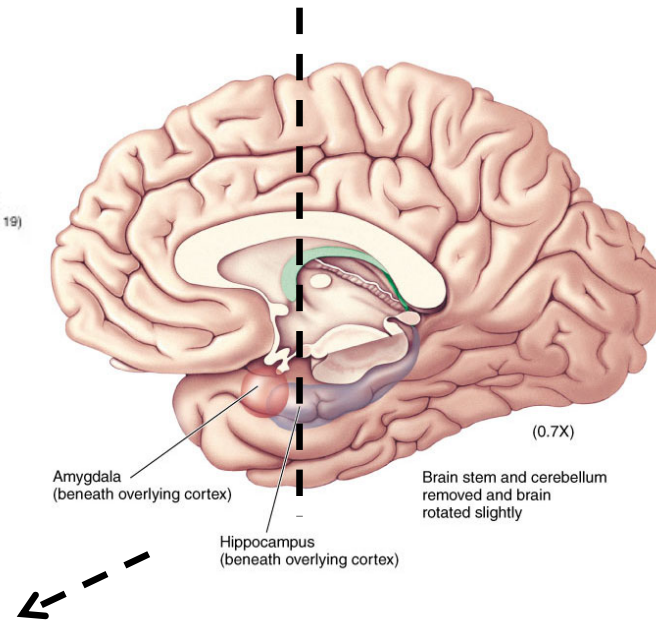


Surface médiane

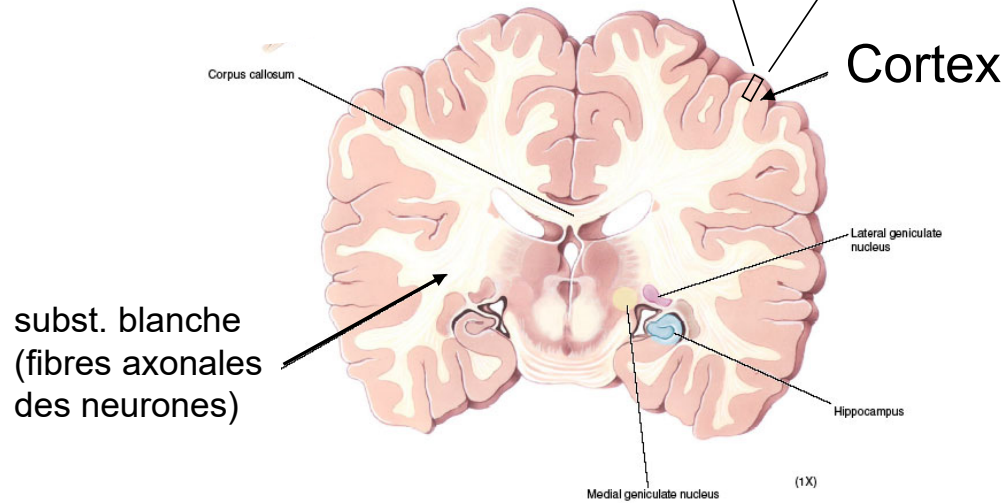
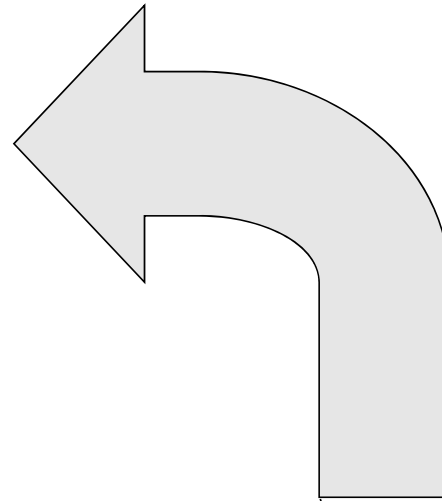
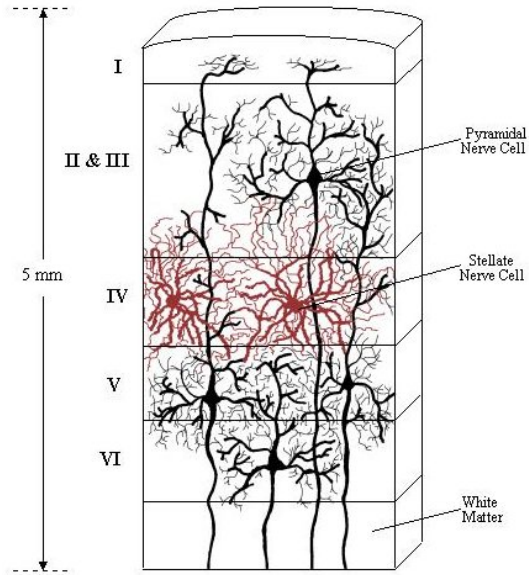
surface
latérale



surface
médiane

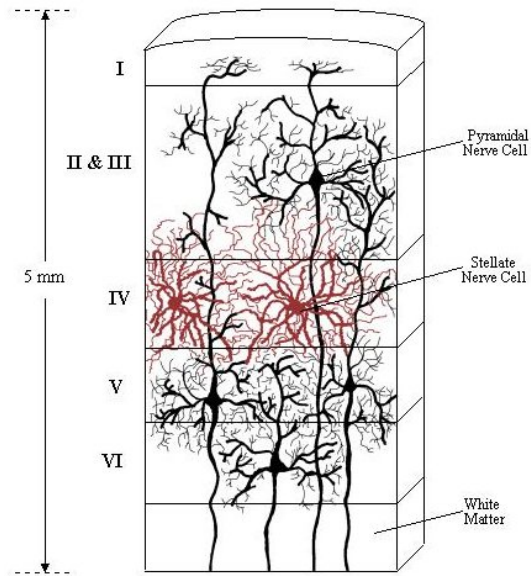


colonne
corticale

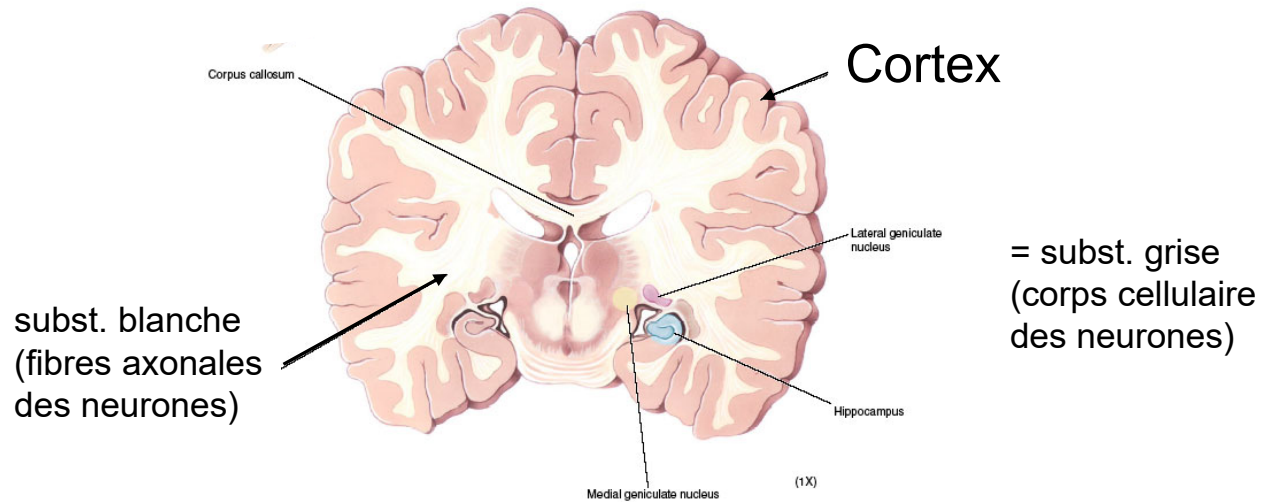
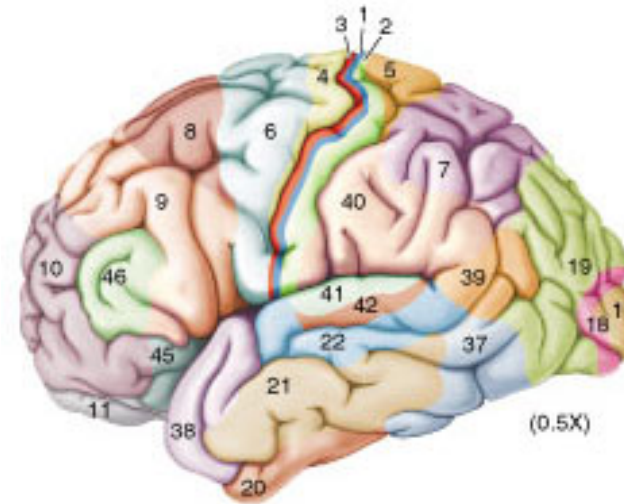


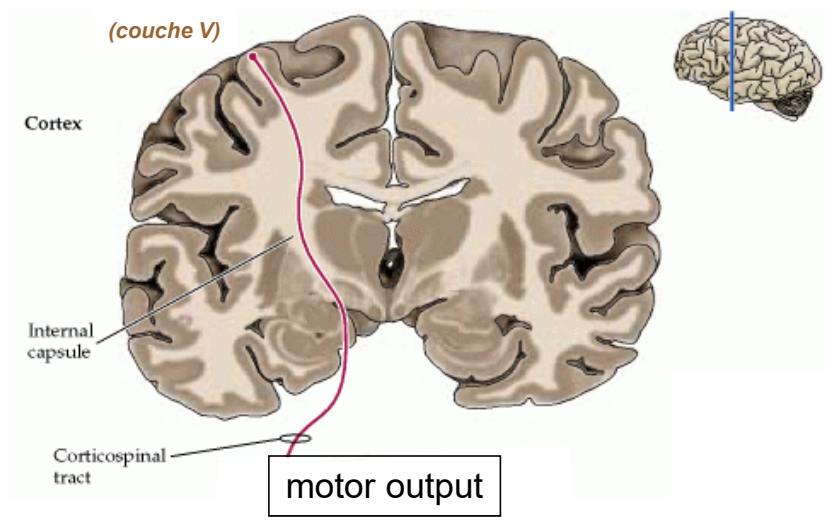
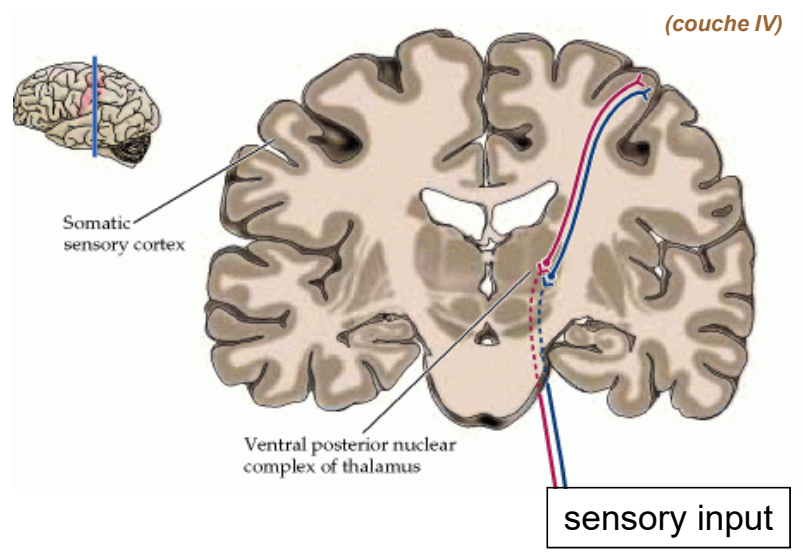
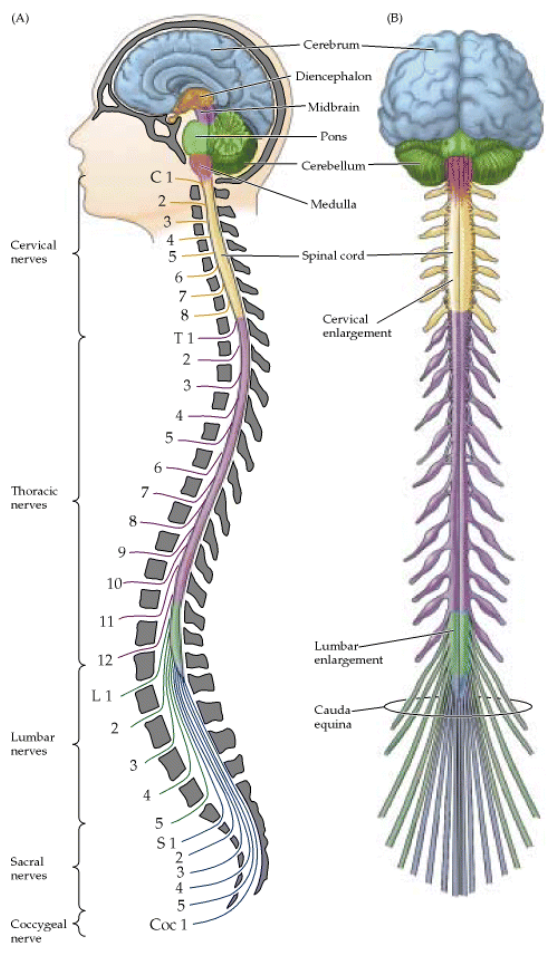
subst. blanche
(fibres axonales
des neurones)

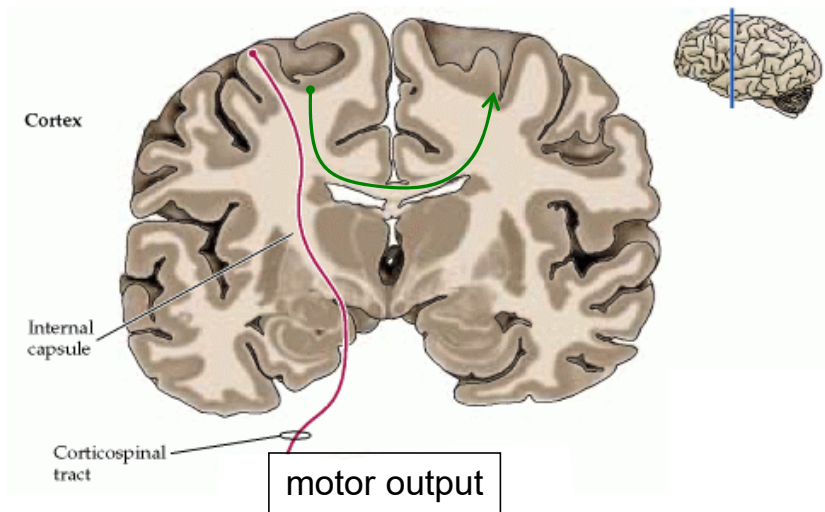
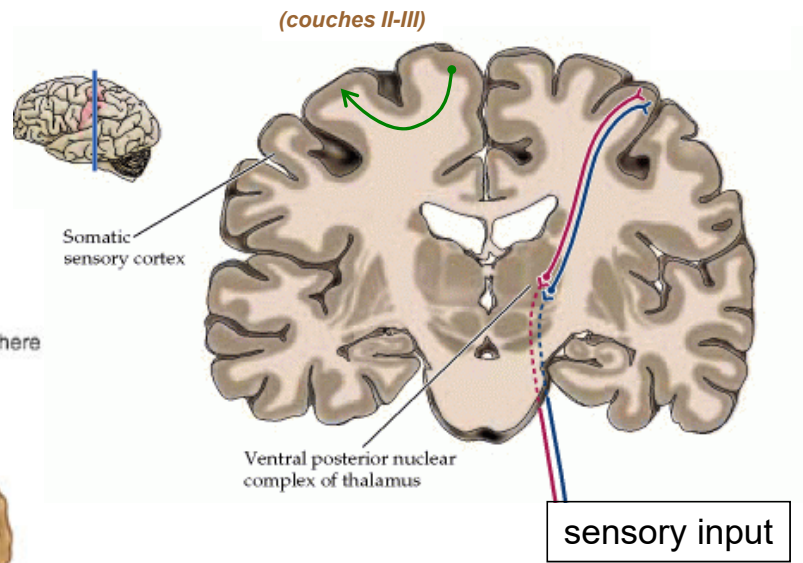
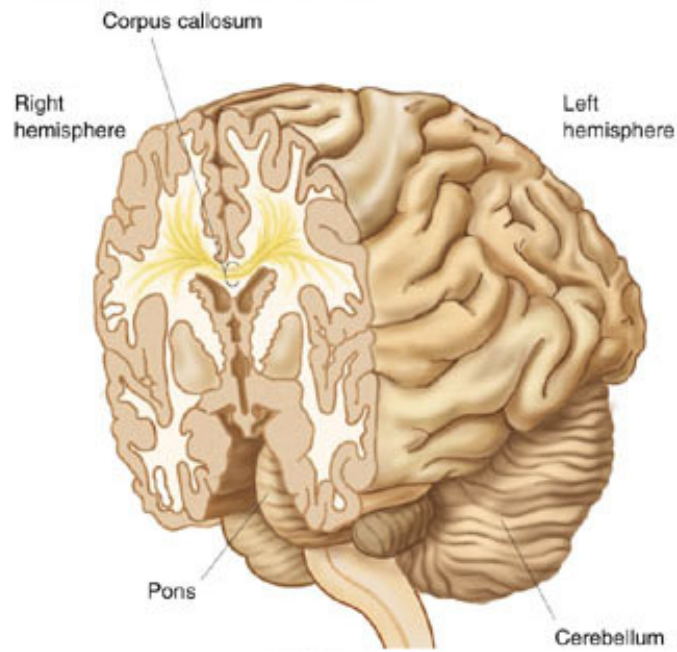
= subst. grise
(corps cellulaire
des neurones)



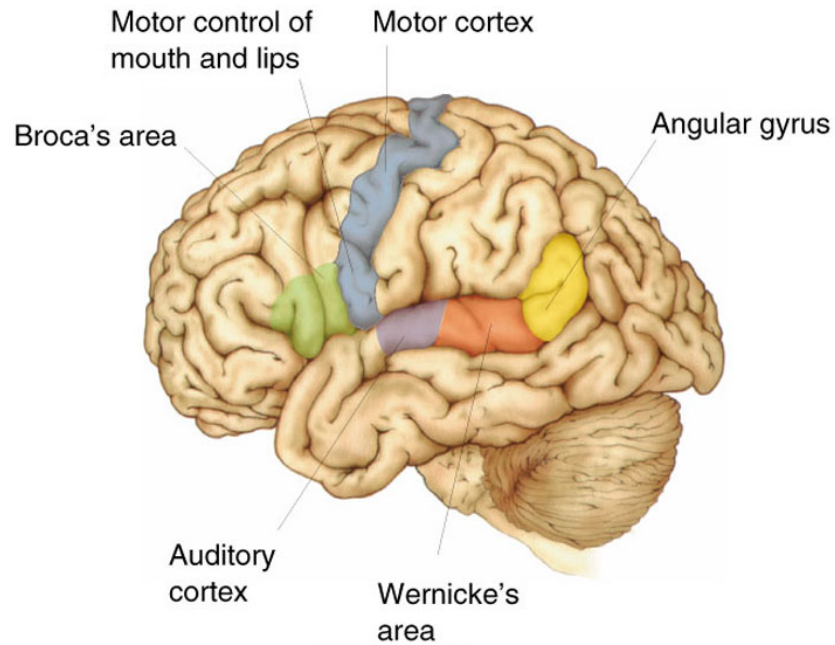
Aires cyto-architectoniques de Brodmann:



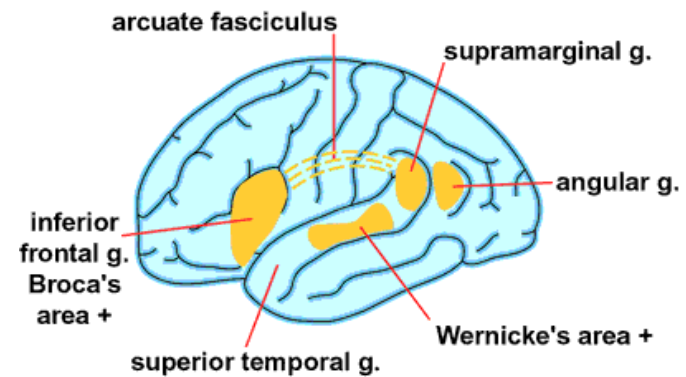




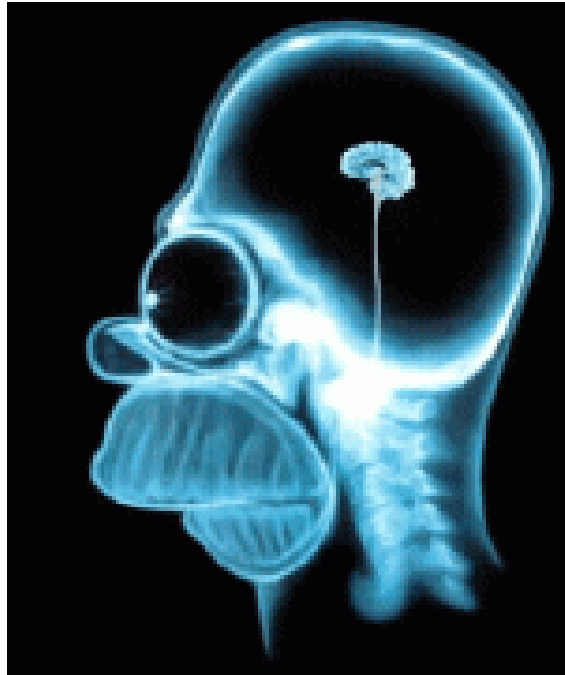
Brefs rappels de Neuro Anatomie



Réseau du langage: aires corticales et connections cortico- corticales



Neuro-imagerie: pour quoi faire?



Importance et applications de la neuro-imagerie

"Une image vaut 1000 mots"

- structure normale du système nerveux
 - développement, dégénérescence (atrophie)
 - pathologies lésionnelles ou autres
-
- activité physiologique et métabolique
 - fonctions / dysfonctions neuronales

→ **in vivo !**

Importance et applications de la neuro-imagerie

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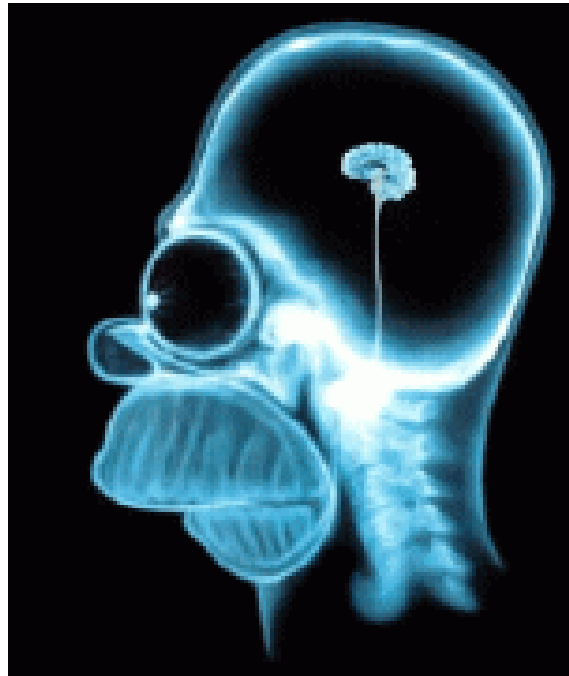
imagerie structurelle

- activité physiologique et métabolique
- fonctions / dysfonctions neuronales

→ in vivo !

imagerie fonctionnelle

Neuro-imagerie: comment faire?

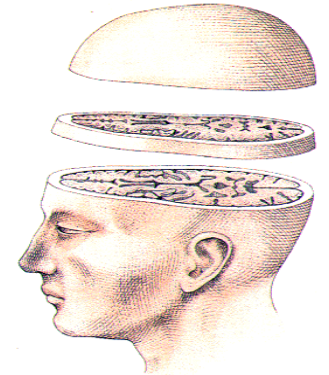


Les secrets du cerveau sont bien protégés

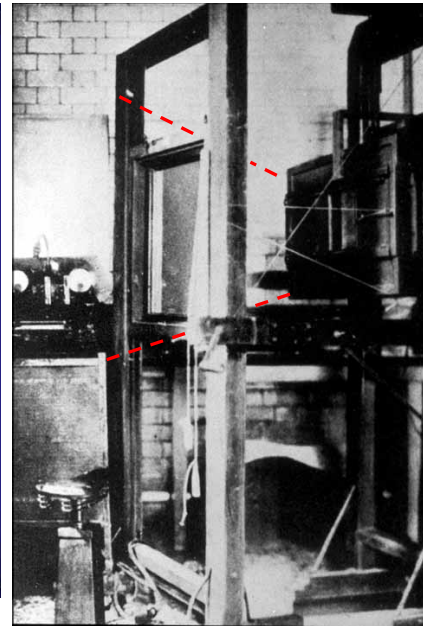
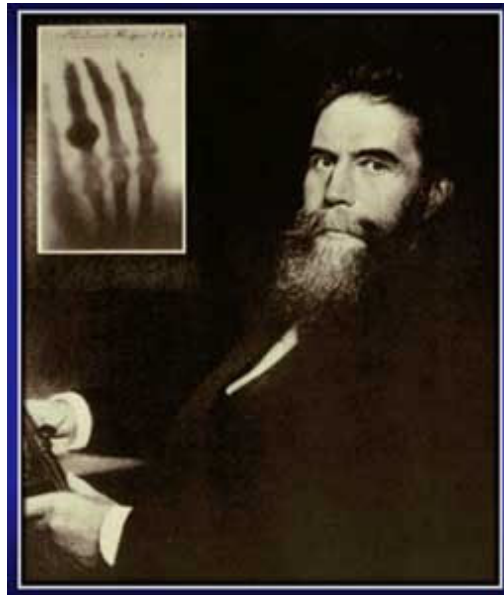


Nombreuses techniques

- Radiographie conventionnelle (RX) et variantes: ventriculographie, myelographie, angiographie
- CT: tomodensitométrie axiale computerisée
- **IRM / RMN**: résonance magnétique nucléaire
- **SPECT**: single-photon computerized tomography, **PET**: positron emission tomography
- et aussi: **EEG** (électro-enchéphalographie), **MEG** (magnéto-enchéphalographie)
- (etc: NIRS, fUS)



Un peu d'histoire



Wilhelm Conrad Röntgen

découvre la radiographie par rayons X en 1895 ("roentography"), prix Nobel de physique en 1901

Un faisceau de rayons X traverse les tissus mais est atténué par la densité des structures rencontrées au passage (tissus durs, os > tissus mous, eau) :

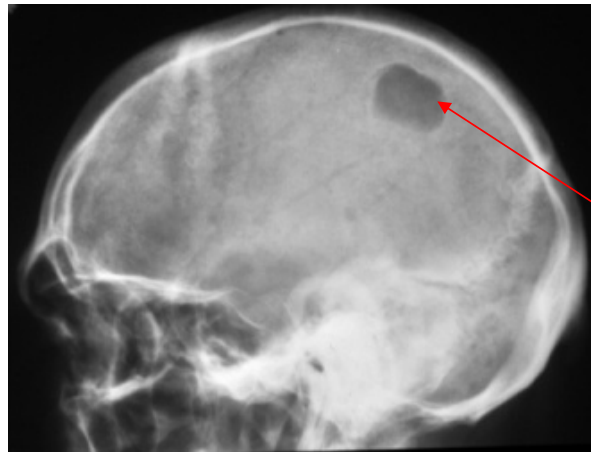
l'image projetée sur un film radio-sensible reflète la géométrie et l'opacité des "obstacles" aux rayons.



fracture

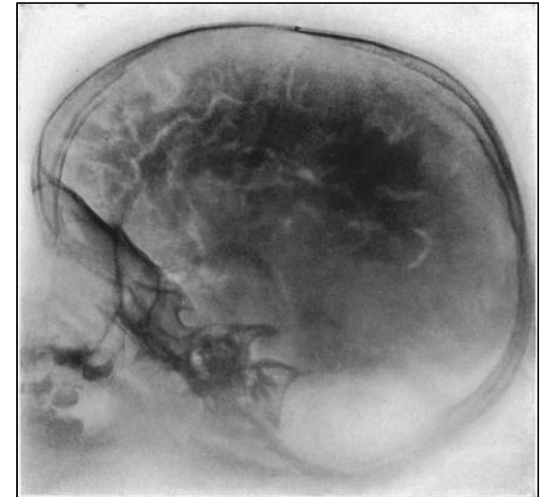


corps étrangers



érosion

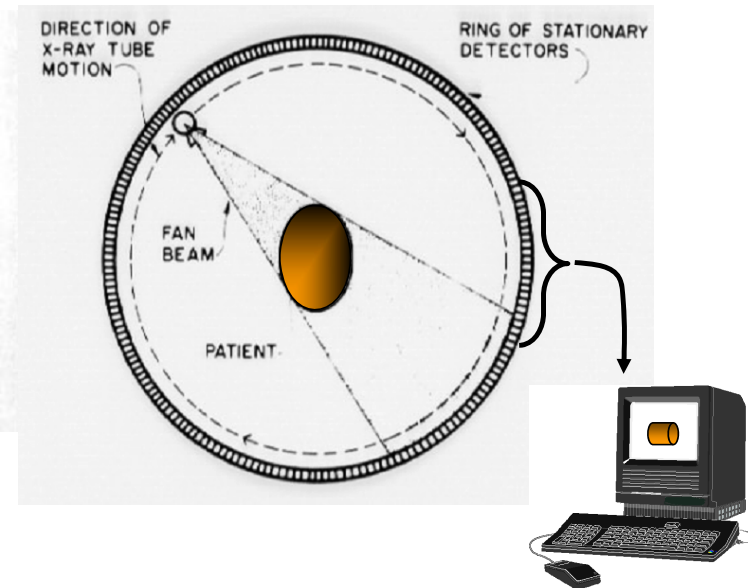
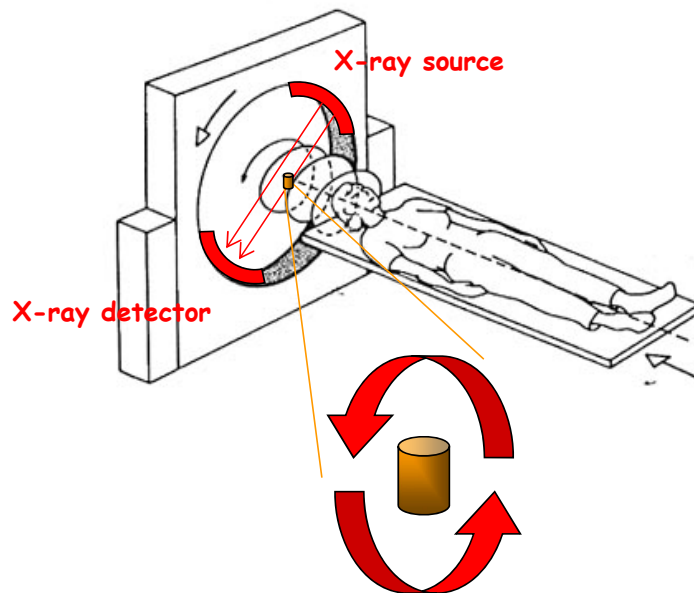
pneumo-encéphalographie
(ventriculo-encéphalographie)



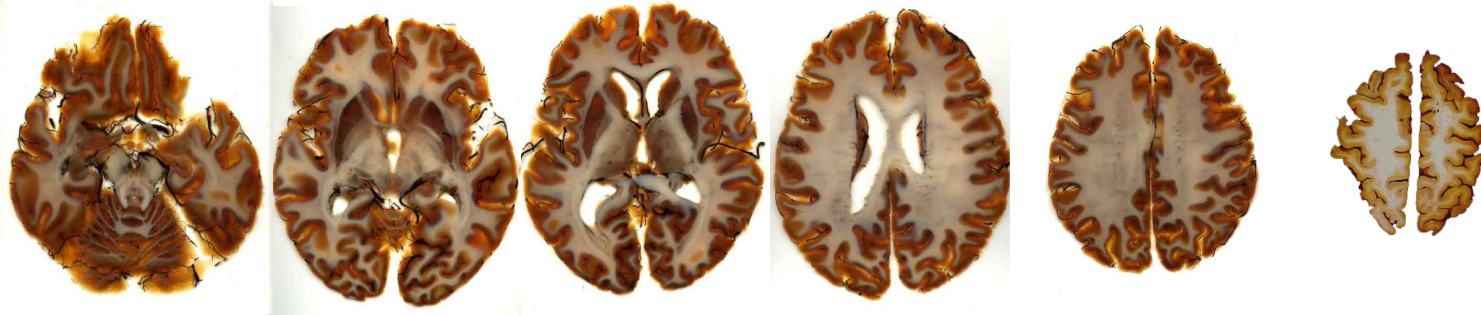
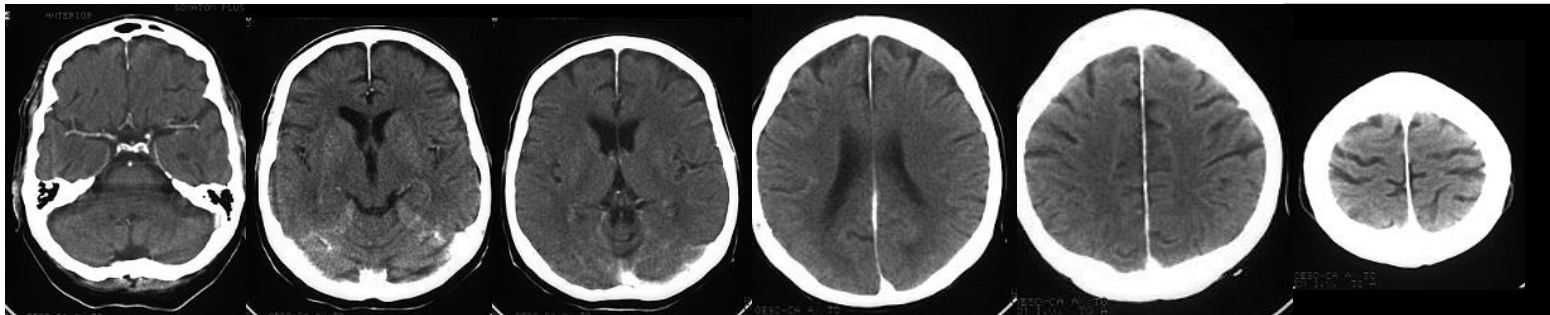
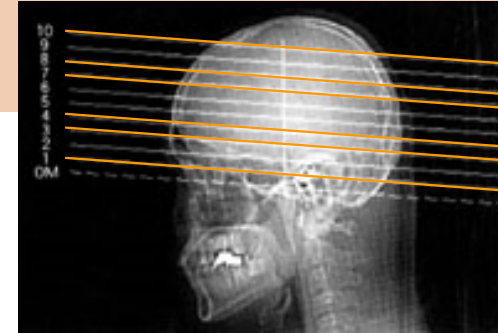
CAT scan: tomo-densitométrie computerisée



- Mis au point par **Godfrey Hounsfield** en 1971, prix Nobel de physiologie & médecine 1979
- Rotation de la source de rayons X autour de l'objet \rightarrow l'image projetée selon différents angles de vue permet une reconstruction 3D (degré d'atténuation = densité à chaque point du volume = contraste de l'image)



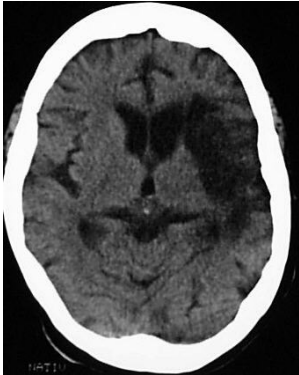
CAT scan



Mr X, 60 ans, hémiparésie droite...



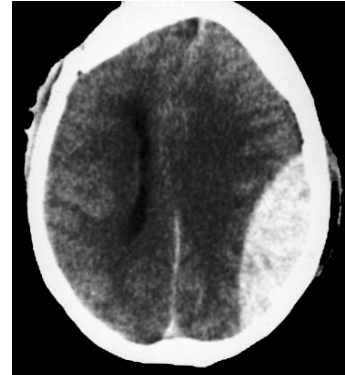
ischémie cérébrale?



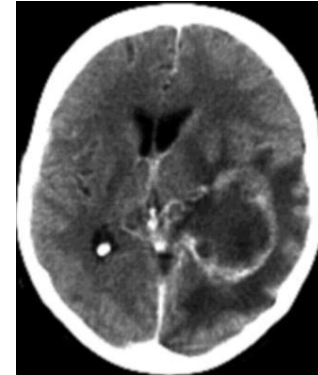
hématome cérébral?



hématome méningé?

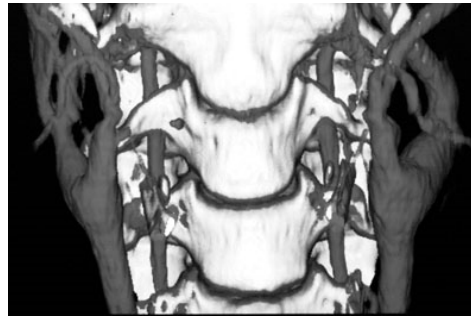
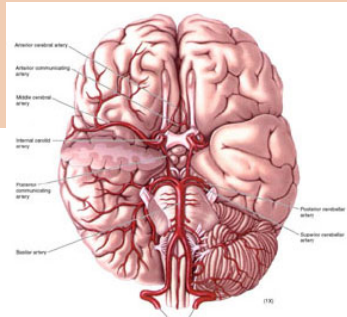


tumeur?



- importance pour diagnostic, traitement...

CAT scan

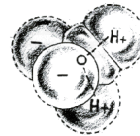


- reconstruction 3D possible
- reste meilleur pour tissus durs, à fort contraste
- avec injection iv de produit de contraste: *angiographie*

IRM: résonance magnétique



- Felix Bloch et Edward Purcell, 1946: énergie électromagnétique absorbée par protons → ré-émission avec fréquence d'onde spécifique selon intensité du champ magnétique appliqué (Prix Nobel physique 1952)
- 2/3 des tissus vivants = H_2O = 2 protons



Raymond Damadian, 1971: RMN pour de différencier tissus (eg, cancer)



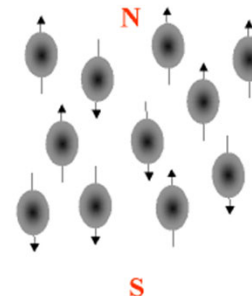
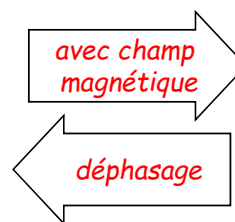
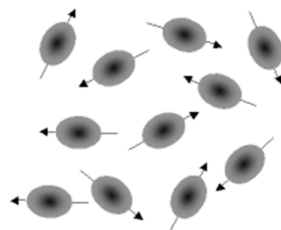
Paul Lauterbur, 1973: gradient dans champ magnétique → contraste entre structures avec différentes "densité" d'eau



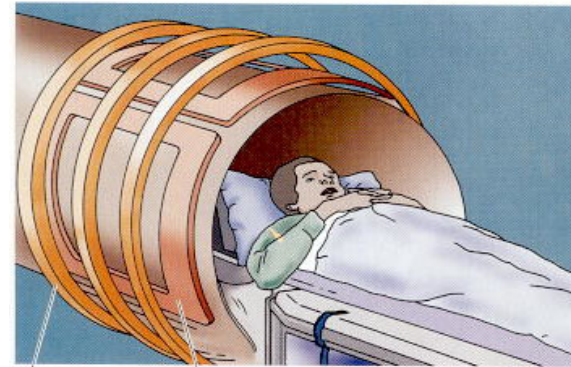
Peter Mansfield, 1977: différences de résonance dues à la distribution de gradients → localisation et création d'image (EPI)

(Prix Nobel médecine & physiologie 2003)

NB - Richard Ernst (CH): encodage par phase et fréquence, spectroscopie RMN, Nobel 1991
- Kurt Wüthrich (CH): structure 3D des macromolécules par spectroscopie RMN, Nobel 2002



IRM: résonance magnétique



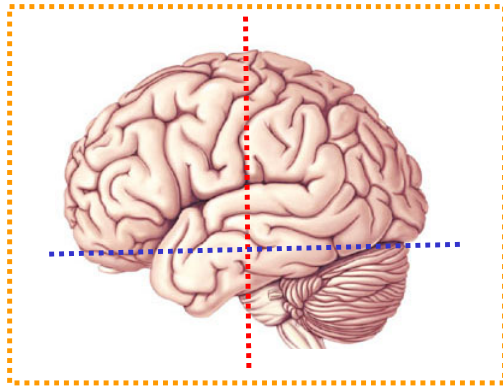
Magnetic coils that produce a static magnetic field in the long axis of the patient

Magnetic coils that produce a static field perpendicular to the long axis

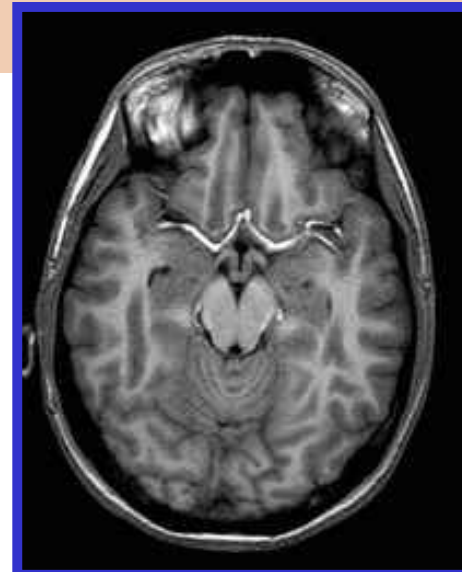
A radiofrequency coil specifically designed for the head or other body part (not shown) perturbs the static fields to generate an MRI

- Champ magnétique: 1.5 - 3.0 Tesla
 - jusqu'à 7 T c/o homme, 14 T c/o animal
 - champ terrestre = 50 microT
- \uparrow champ \rightarrow \uparrow signal/contraste & \uparrow résolution spatiale

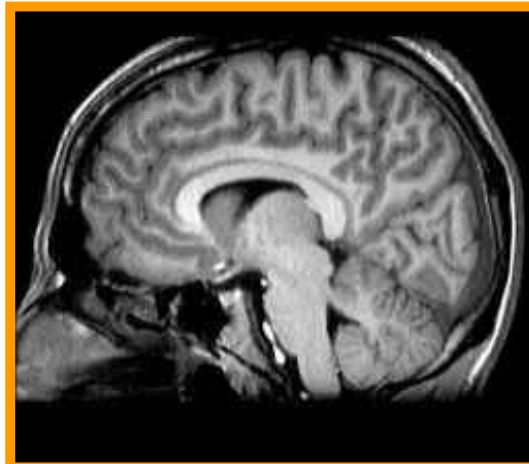
IRM: résonance magnétique



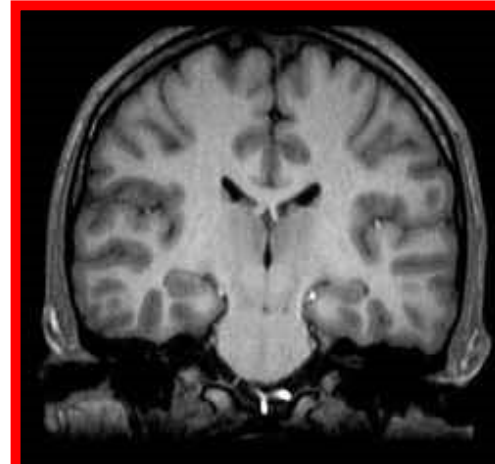
resolution ~ 1mm



coupe
axiale



coupe sagittale

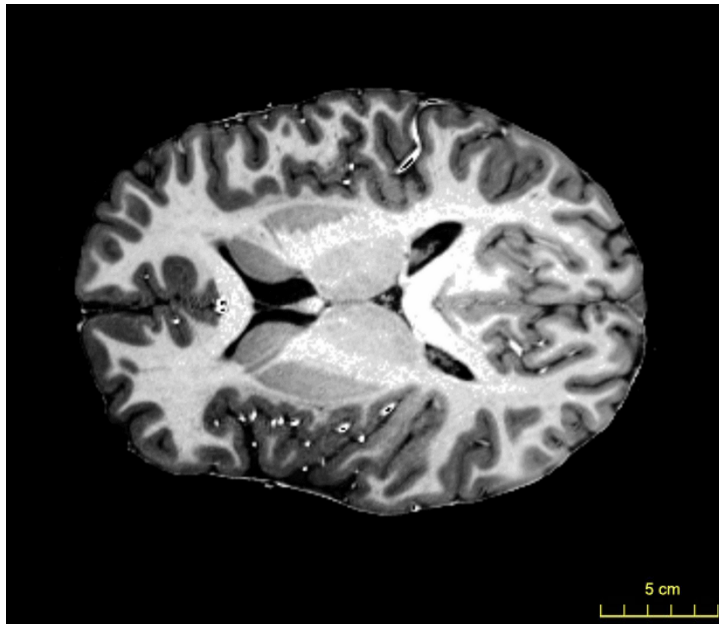


coupe
coronale



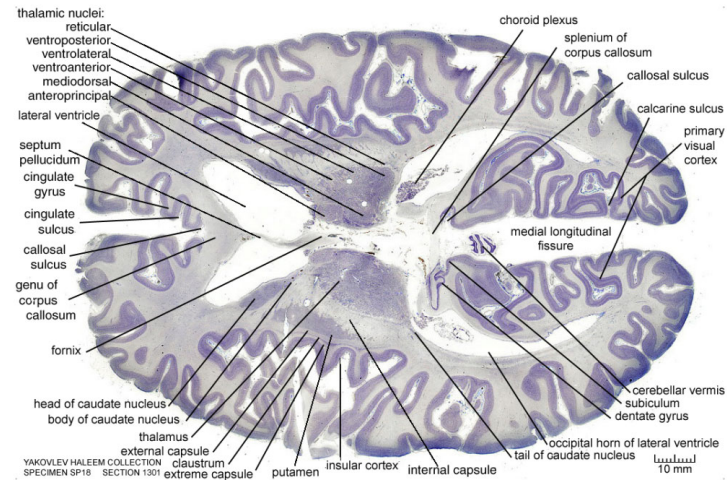
IRM / Histologie

IRM 3T



resolution $\leq 1\text{mm}$

Histologie

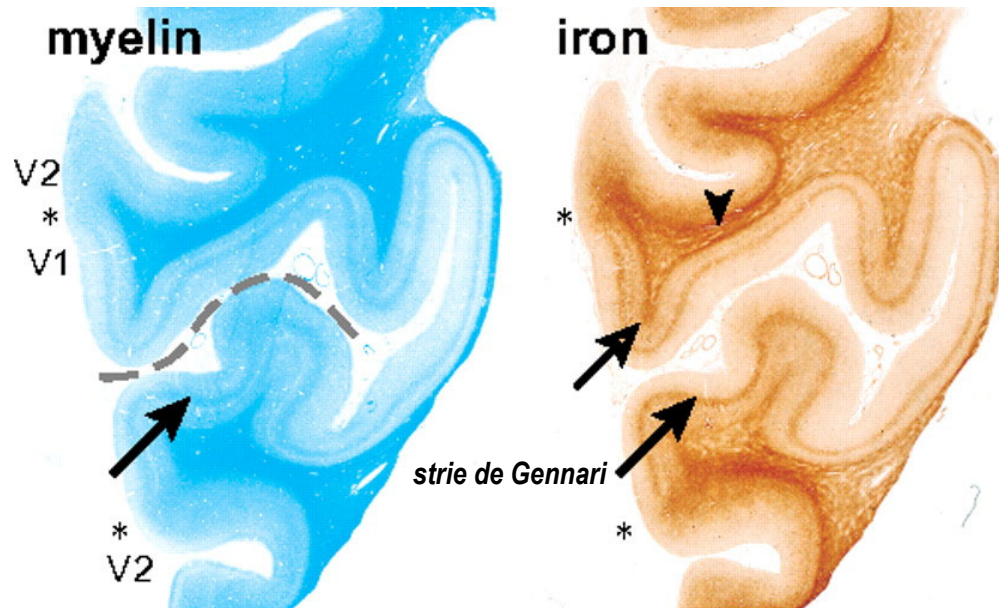


See Navigable Atlas of the Human Brain
<http://www.msu.edu/>

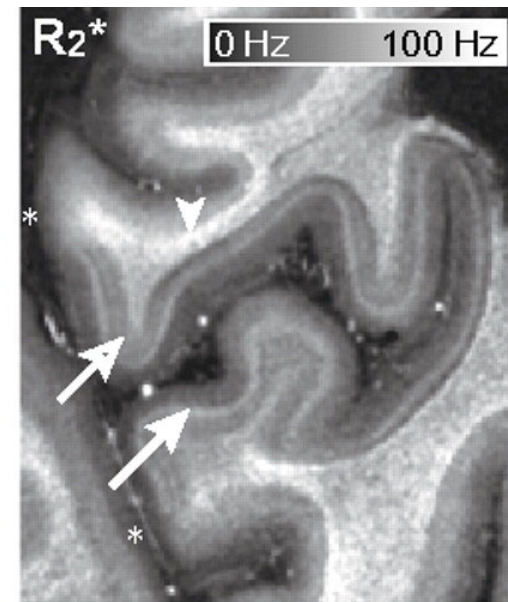
Keith D. Sudheimer, Brian M. Winn, Jay M. Shoaps, Kristina K. Davis,
Archibald J. Fobbs Jr., and John I. Johnson
Radiology Department, Communications Technology Laboratory,
and College of Human Medicine, Michigan State University;
National Museum of Health and Medicine.

IRM / Histologie

Coupes histologiques (+ colorations)

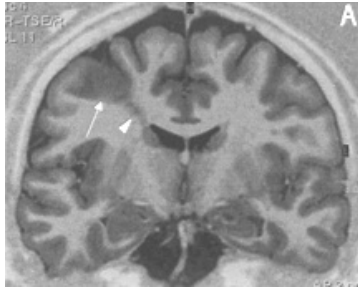


Coupes IRM 7T (haute resolution 150 μm)

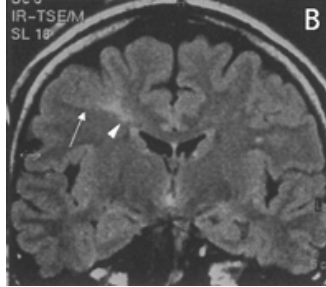


**/* limite entre les aires V1/V2*

Anomalies



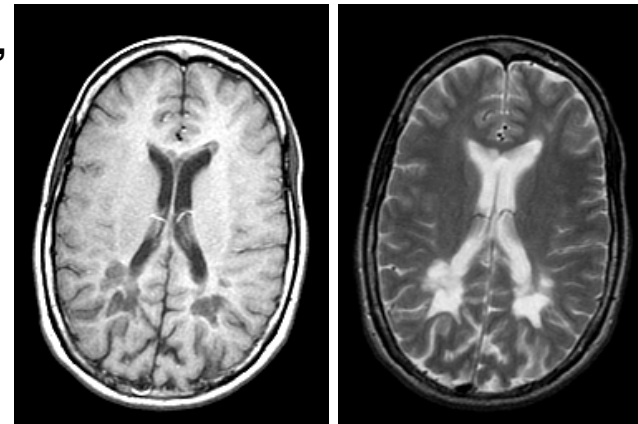
T1



T2 FLAIR

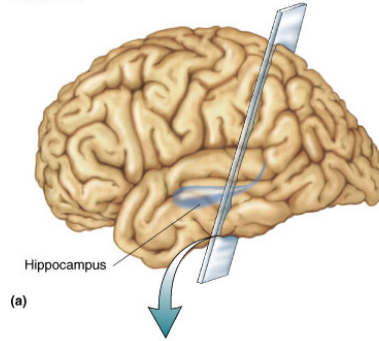
**anomalie de la substance grise,
ex: dysplasie corticale**

**anomalie de la substance blanche,
ex: démyélinisation lors de
sclérose en plaques**

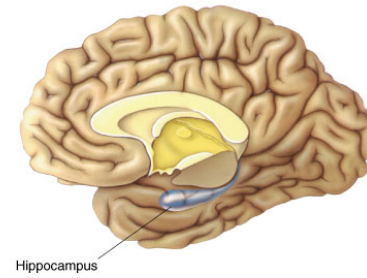




Lateral view

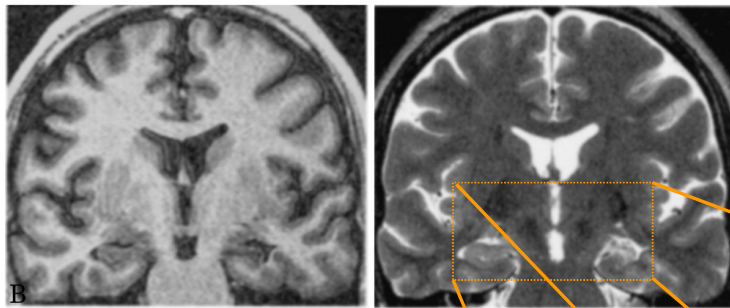
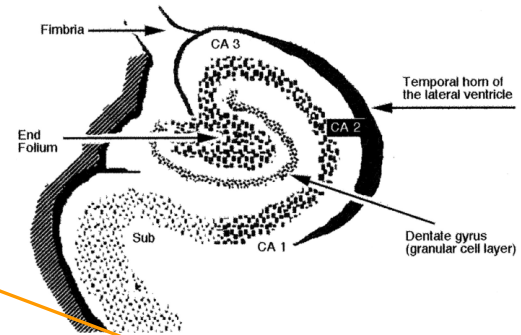


Medial view



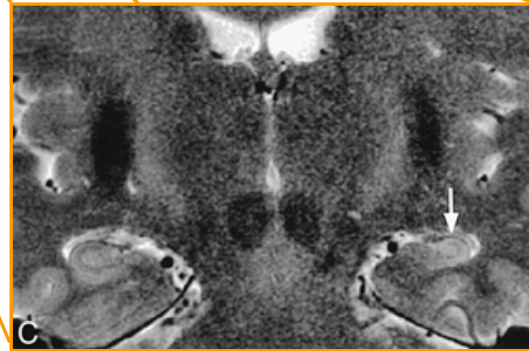
(a)

Normal Hippocampal Structure



B

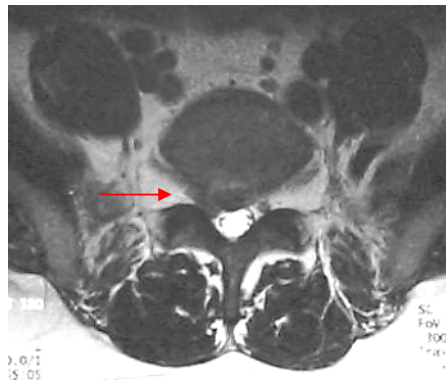
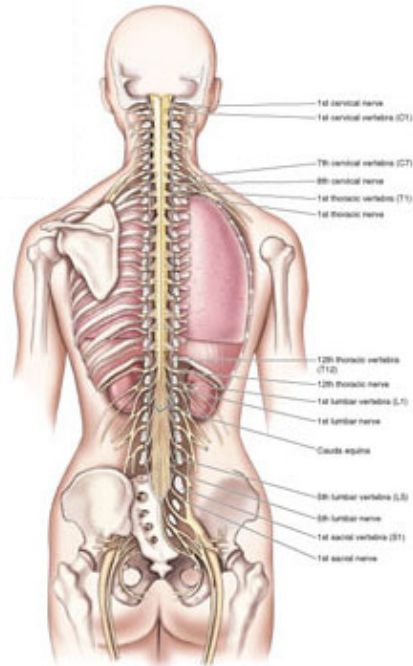
Sclérose
hippocampique
et épilepsie



C



IRM



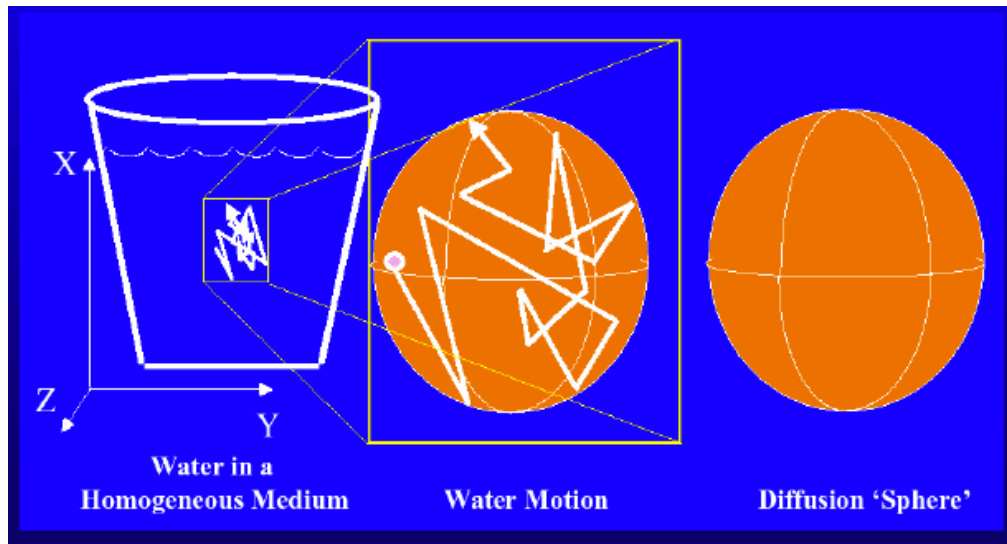
IRM: multiples variantes

- anatomique: T1, T2, FLAIR, etc...
- perfusion, angiographie (injection de contraste)
- diffusion
- fonctionnelle: BOLD (blood-oxygen level-dependent)
- spectroscopie

IRM: multiples variantes

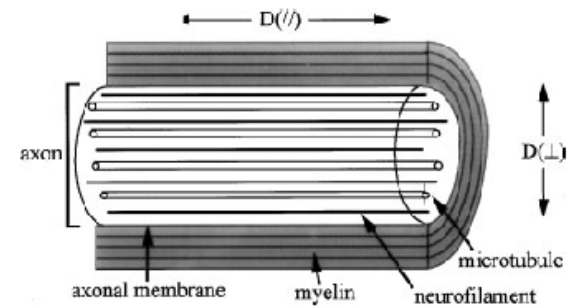
- anatomique: T1, T2, FLAIR, etc...
- perfusion, angiographie (injection de contraste)
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DTI= diffusion tensor imaging

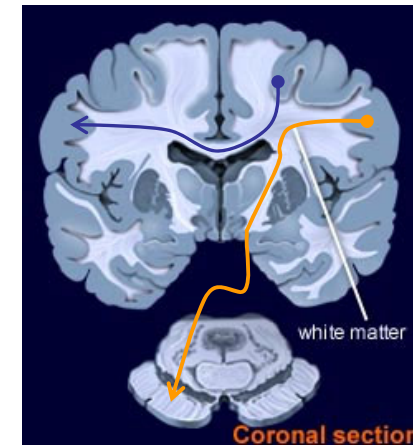
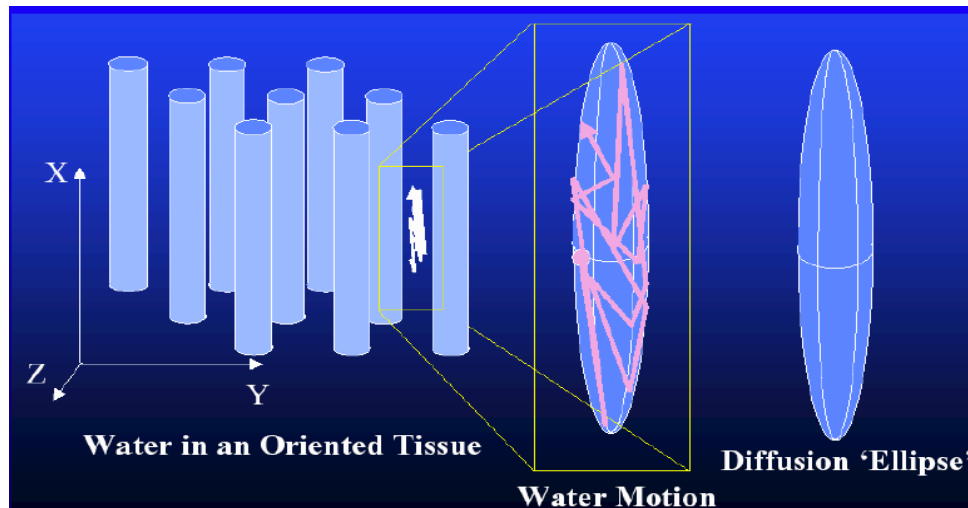


- mouvement spontané des molécules d'eau
- milieu liquide pur = diffusion isotropique
- tissu nerveux / axones = diffusion anisotropique
- tenseur = directions dominantes de diffusion

(appliqué en neuroimagerie par Thomsen et coll, 1987;
Moseley et coll, 1990)

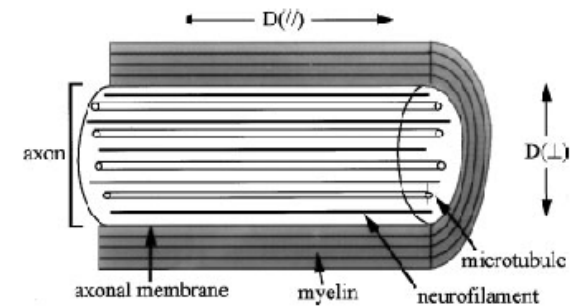


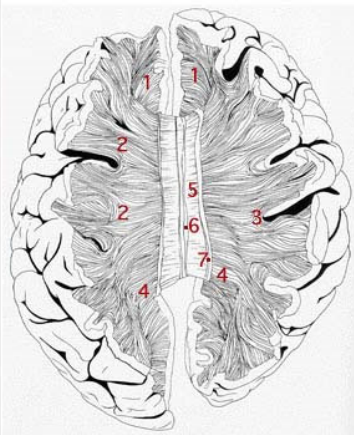
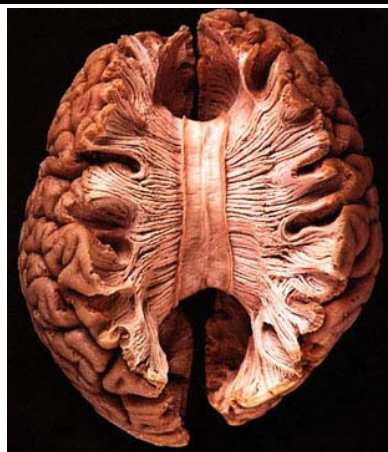
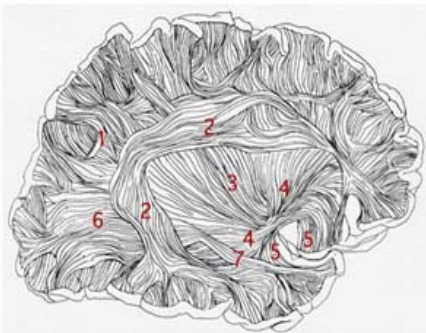
DTI= diffusion tensor imaging



- mouvement spontané des molécules d'eau
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- tenseur = directions dominantes de diffusion

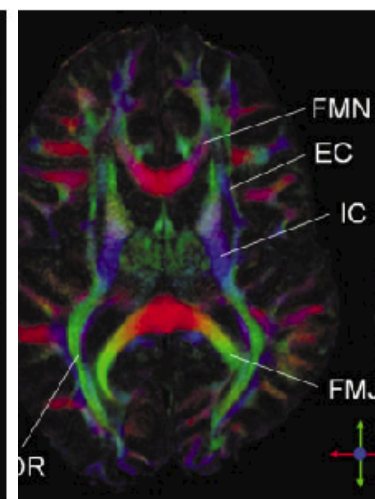
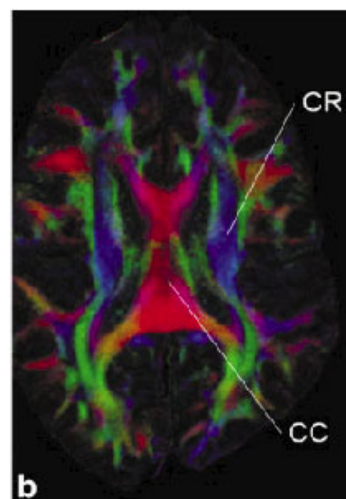
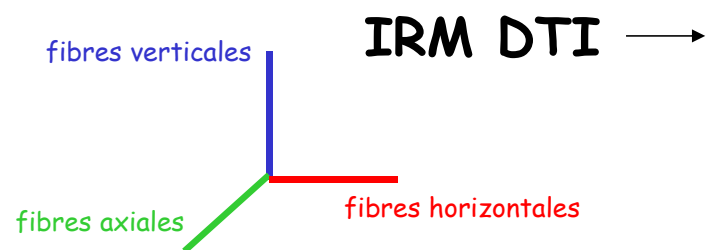
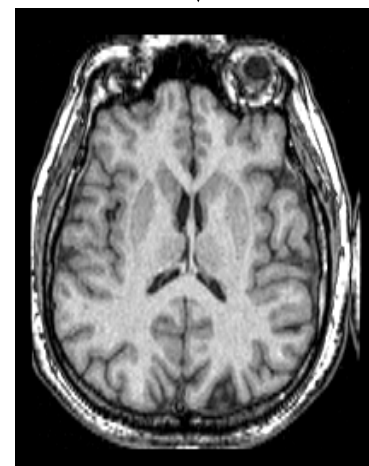
(appliqué en neuroimagerie par Thomsen et coll, 1987;
Moseley et coll, 1990)



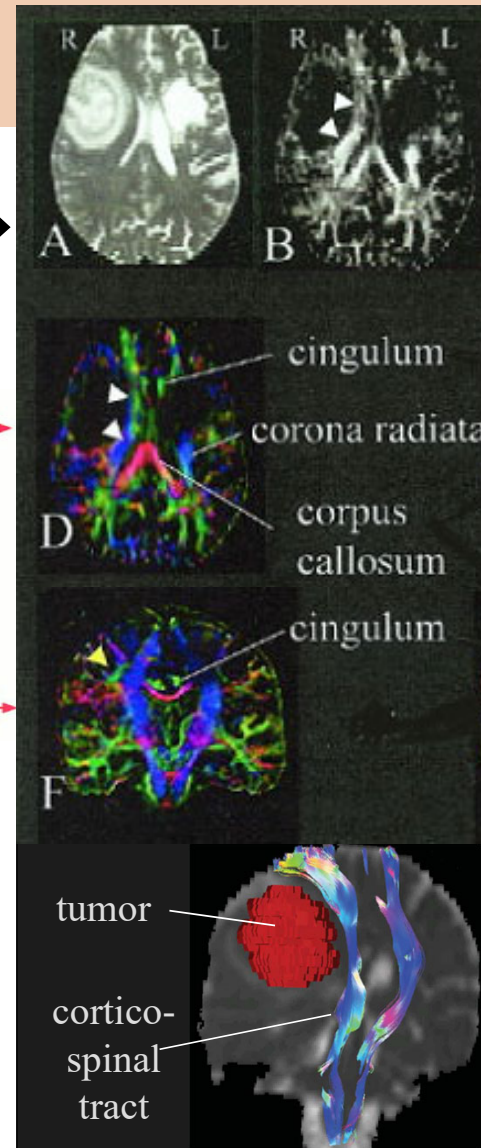
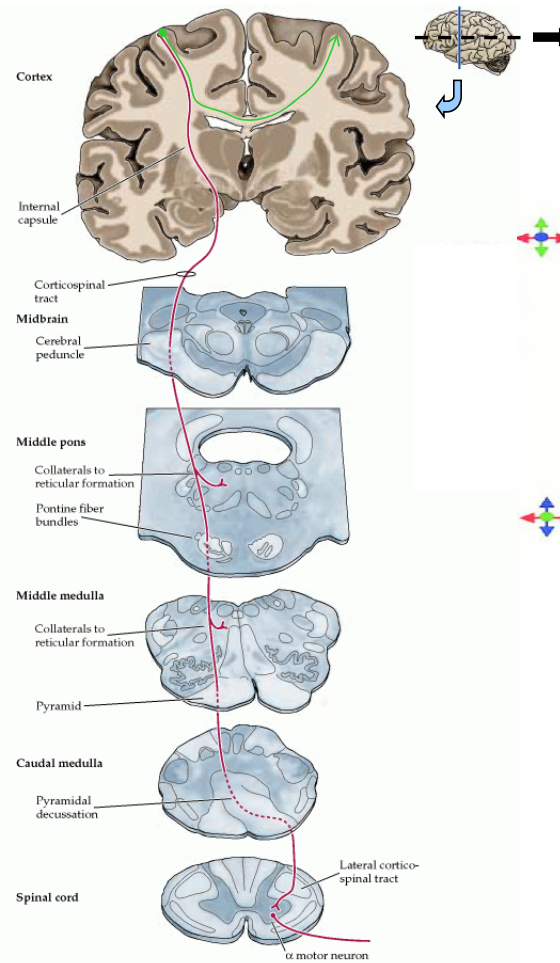
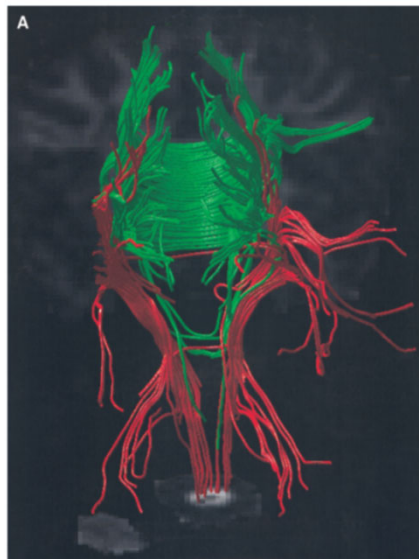
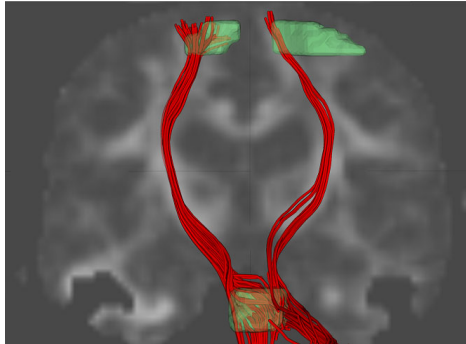


Dissection

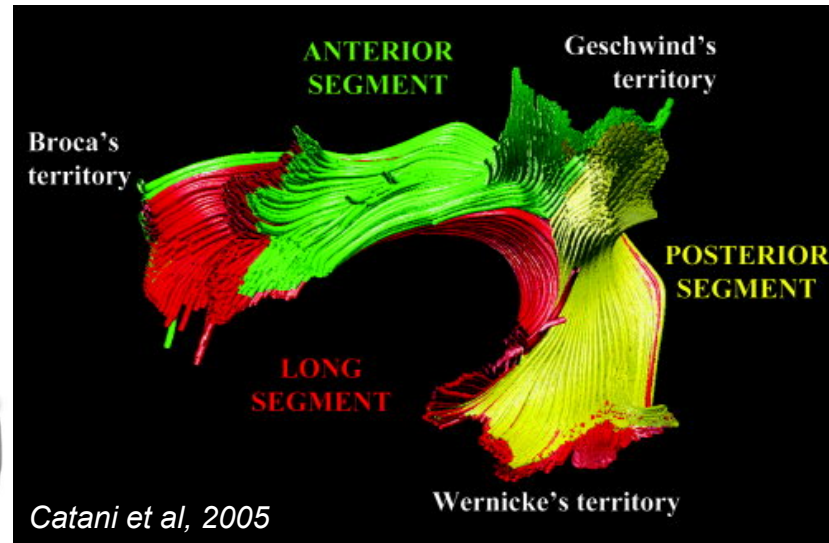
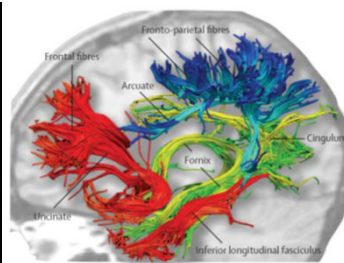
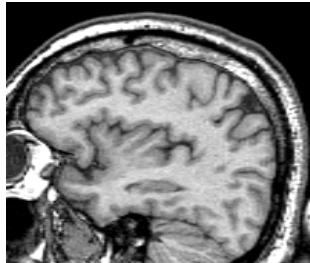
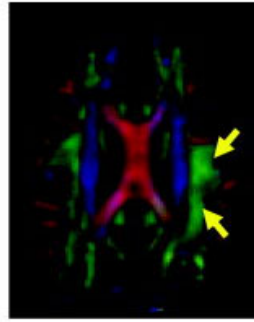
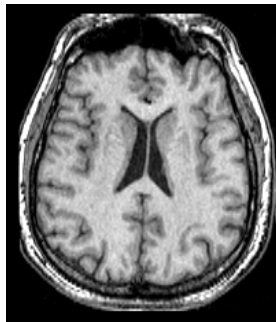
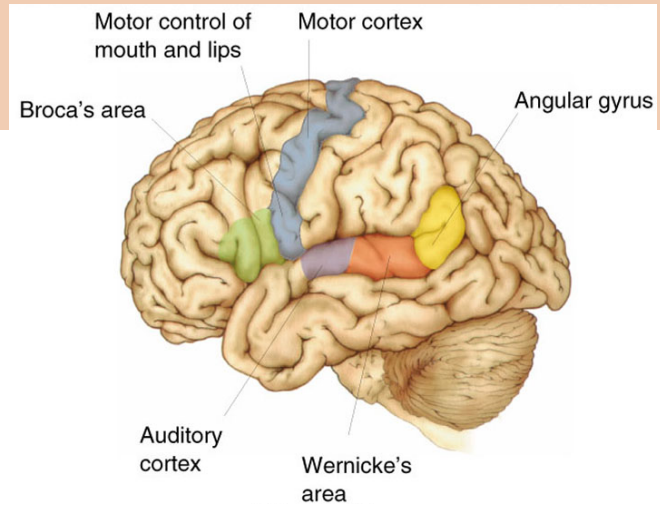
IRM anatomique T1



DTI & tractographie: voies motrices cortico-spinales

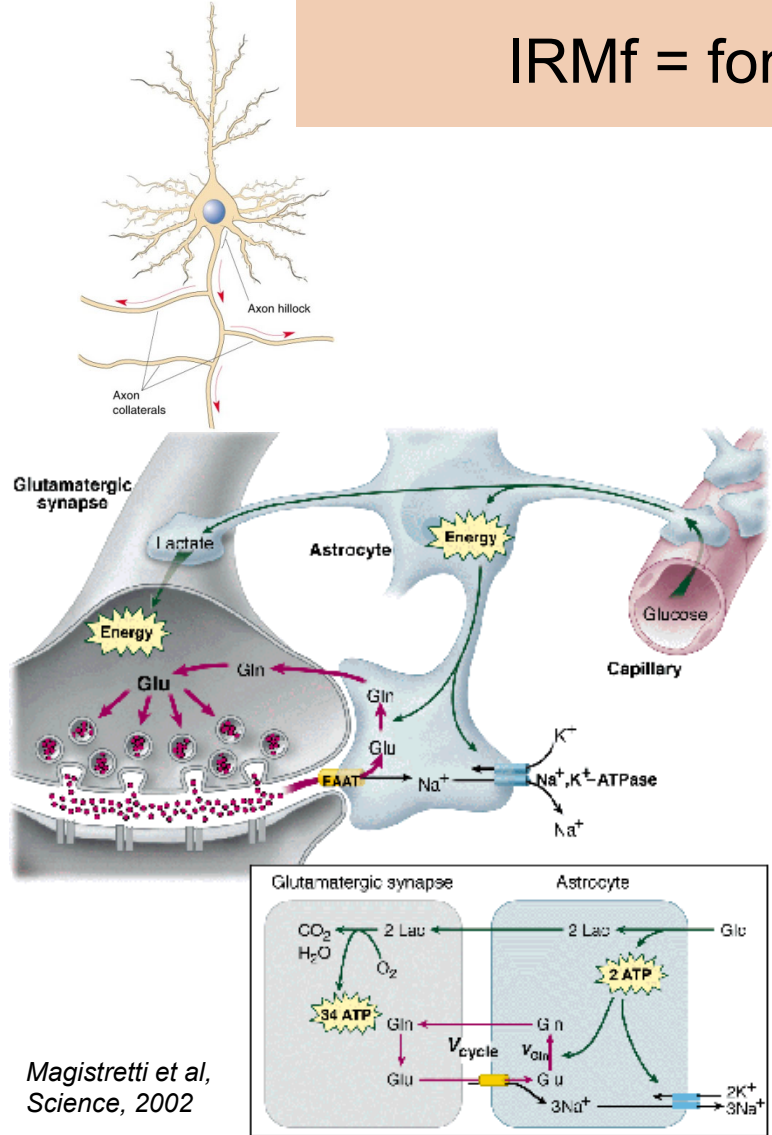


DTI & tractographie: voies du langage oral



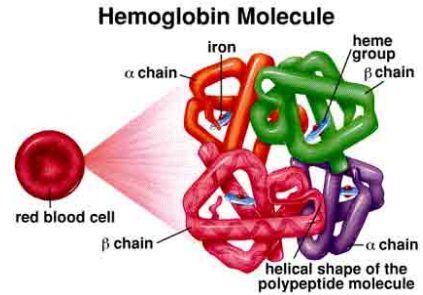
IRMf = fonctionnelle

IRMf = fonctionnelle

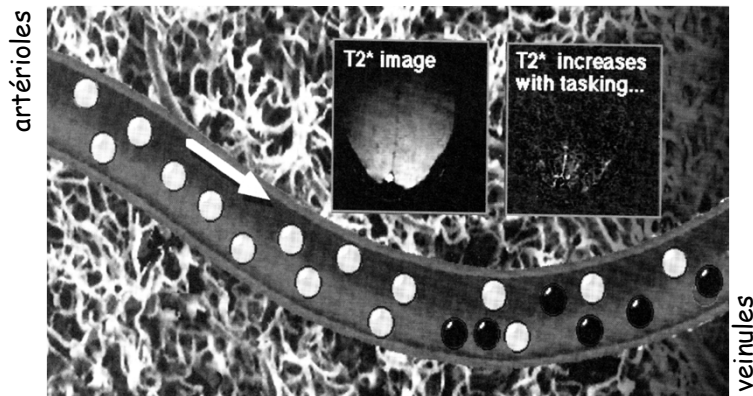
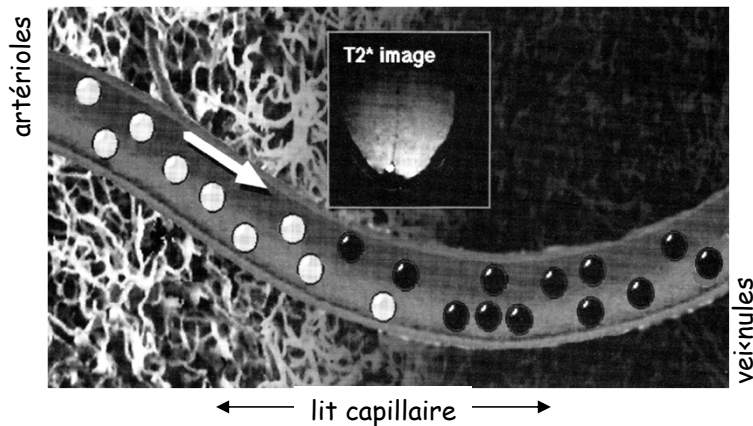


- ↑ activité neuronale
 - ↑ glycolyse:
 - $6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2$
 - ↑ consommation O₂
 - régulation vasculaire
 - ↑ apport → ↑ oxy-Hb
 - ↑ signal IRM T2* = BOLD
- (blood-oxygen level dependent)

Magistretti et al, Science, 2002

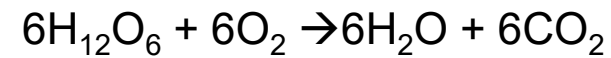


IRMf = fonctionnelle



↑ activité neuronale

→ ↑ glycolyse:



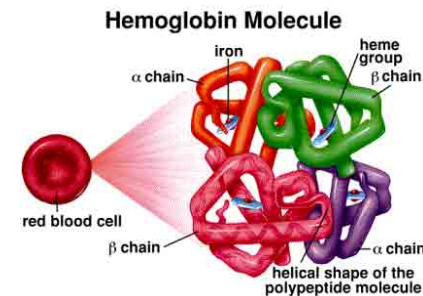
→ ↑ consommation O₂

→ régulation vasculaire

→ ↑ apport → ↑ oxy-Hb

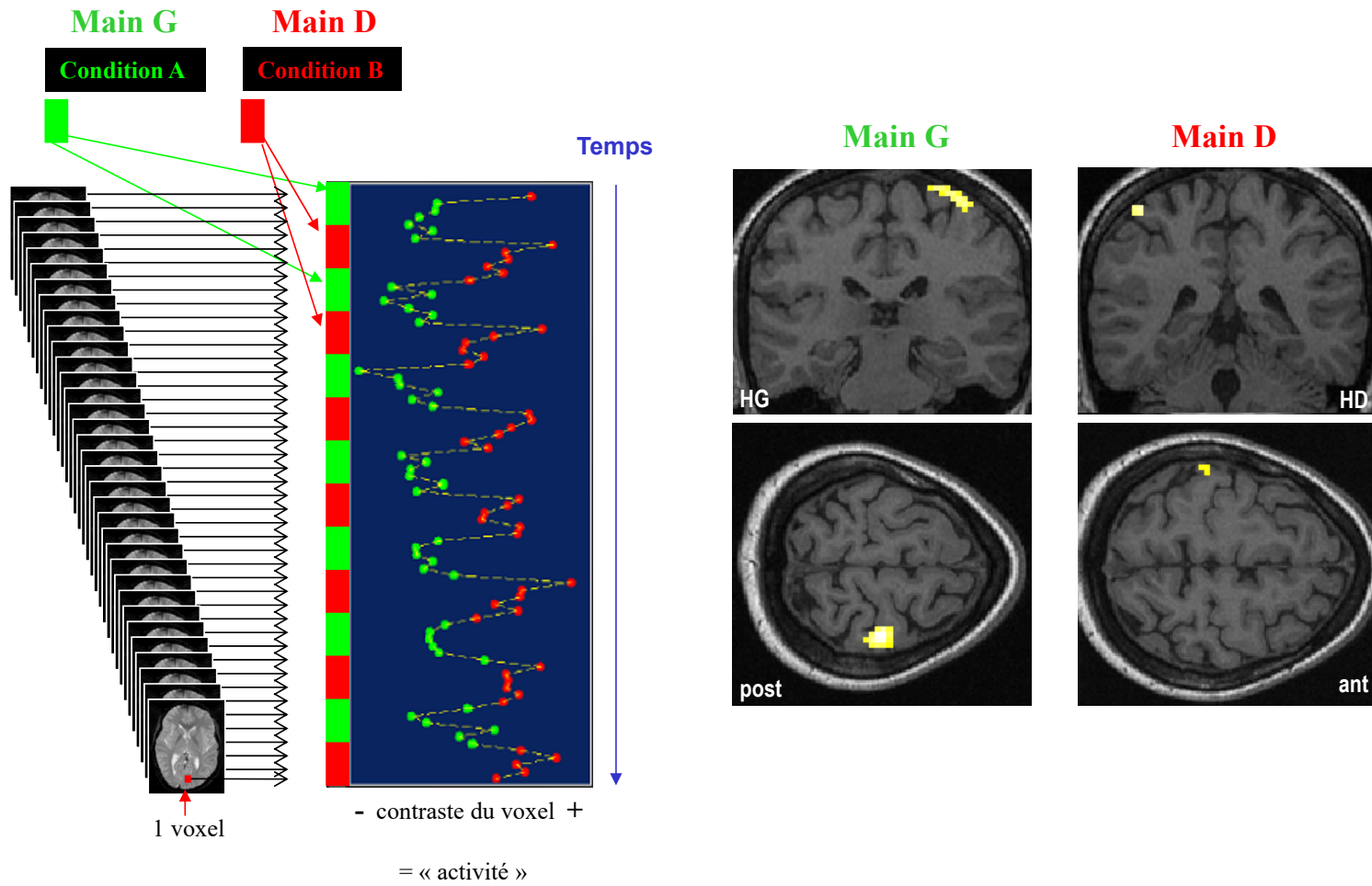
→ ↑ signal IRM T2* = BOLD

(blood-oxygen level dependent)

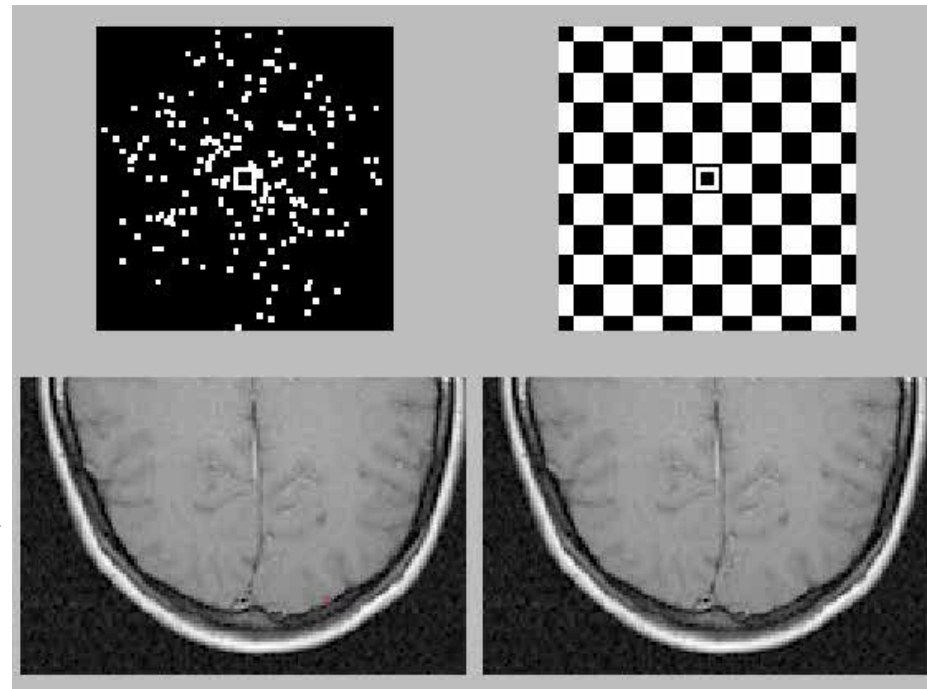
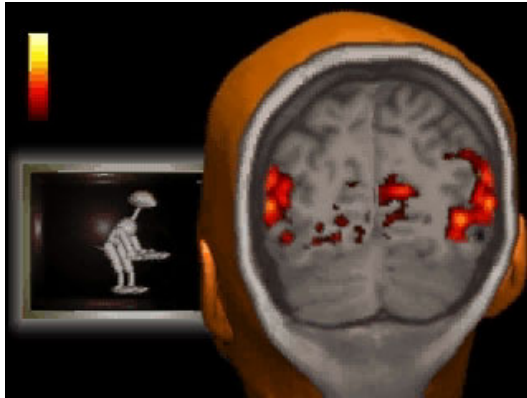
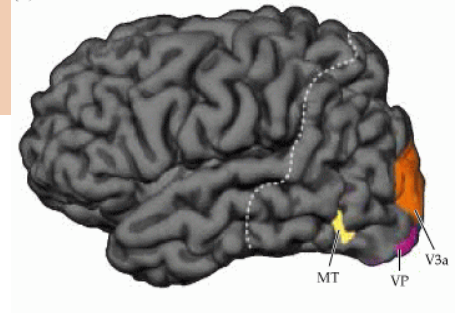


Effet BOLD: découvert par Seiji Ogawa et coll. en 1990

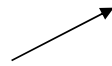
IRMf



IRMf de la vision

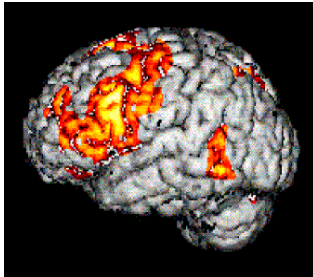


aire V5 / MT



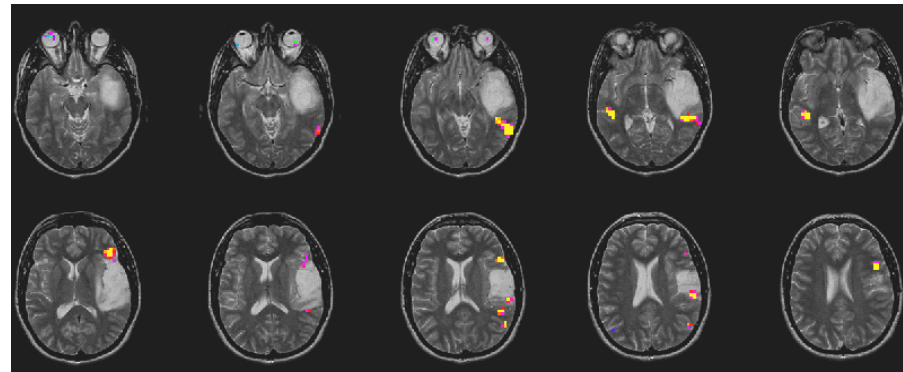
aire V1





*Tâche verbale:
générer un verbe en réponse à un mot entendu
("repas" → "manger")*

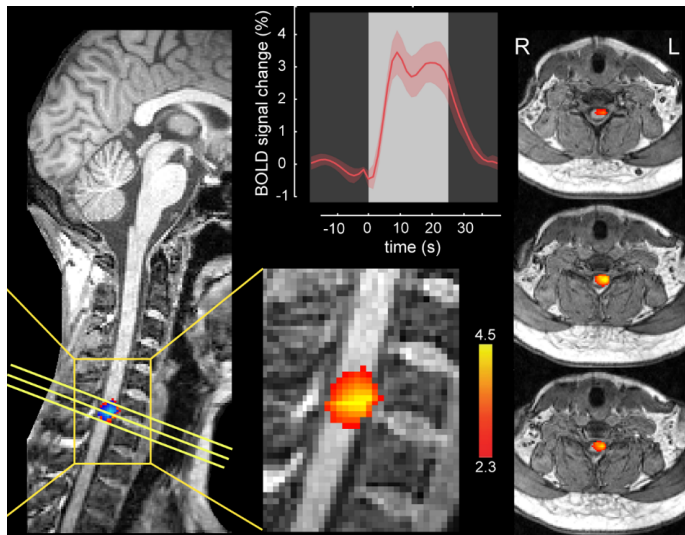
sujet sain:
activation des aires de Broca et Wernicke



patient avec tumeur temporale:
activation péri-lésionnelle + hémisphère opposé

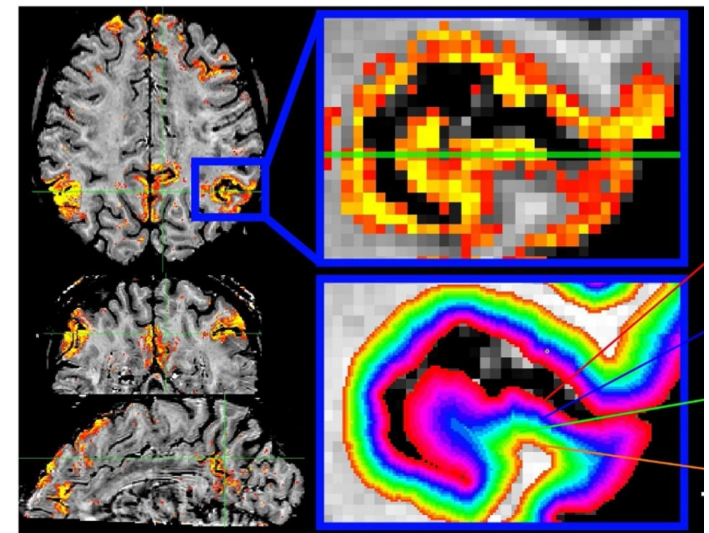


IRMf de la moelle épinière:



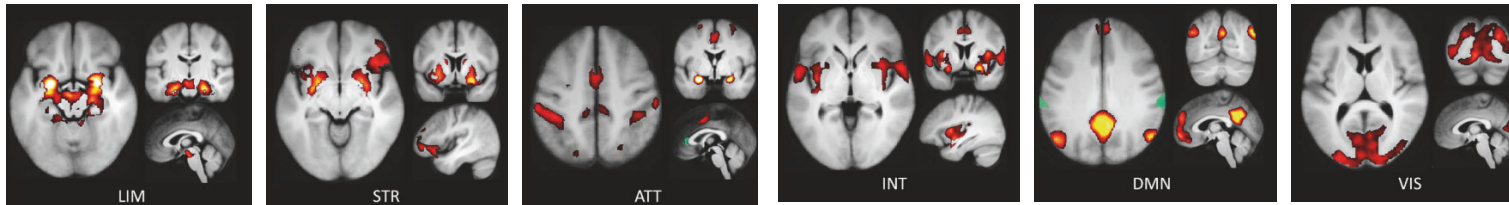
*Ex: motricité, sensibilité, douleur,
fonctions viscérales, ...*

IRMf HR du cortex à 7T:



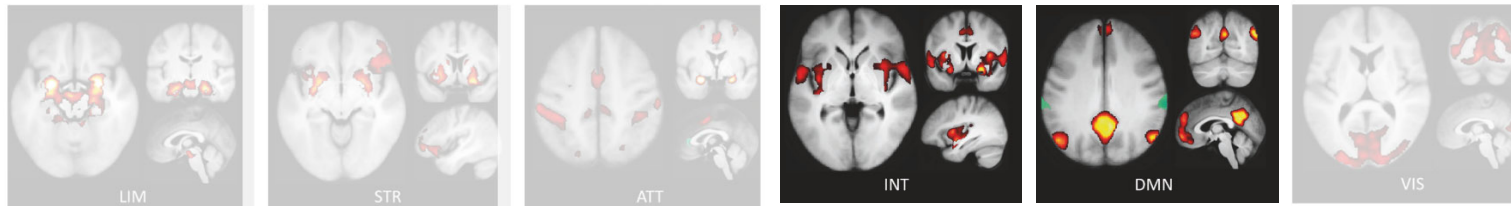
*Ex: couches corticales, afférences
thalamiques ou corticales,
bottom-up vs top-down, ...*

Applications possibles du futur



- Différents **réseaux** cérébraux “intrinsèques” révélés par **co-activations**
- fluctuations spontanées (au repos)
- modifications spécifiques dans certaines **pathologies**: diagnostic? prognostic / risque? traitement?

Applications possibles du futur

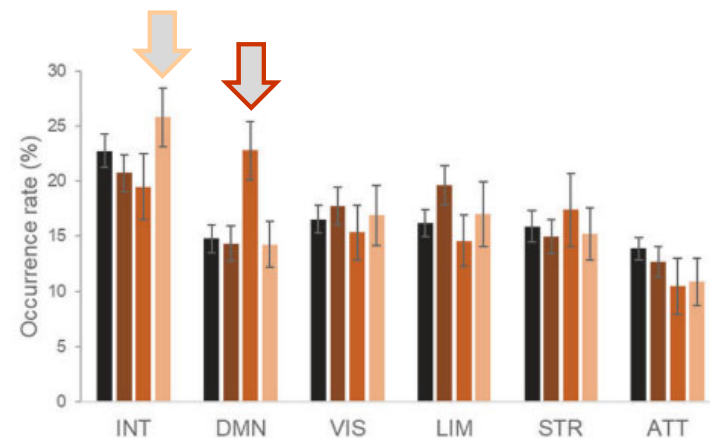


- Différents **réseaux** cérébraux “intrinsèques” révélés par **co-activations**
- fluctuations spontanées (au repos)
- modifications spécifiques dans certaines **pathologies**: diagnostic? prognostic / risque? traitement?
- ex: depression / manie (trouble bipolaire)



IRMf répétées (env. 1x/3 mois)
chez le même groupe de patients (n=20)
pendant 15 mois (total 85 sessions)

■ Controls ■ BD euthymia ■ BD depression ■ BD hypomania



G. Rey et al., NPP 2021

Neuro-imagerie nucléaire

PET = Positron Emission tomography

SPECT = Single Photon Emission Tomography

PET/TEP & SPECT

→ Injection d'isotopes radioactifs

- **PET: positron emission tomography**

^{15}O ($\frac{1}{2}\text{vie} = 2 \text{ min}$)

^{11}C ($\frac{1}{2}\text{vie} = 20 \text{ min}$)

^{18}F ($\frac{1}{2}\text{vie} = 2 \text{ h}$)

+ lié à H_2O , glucose, neurotrans ...

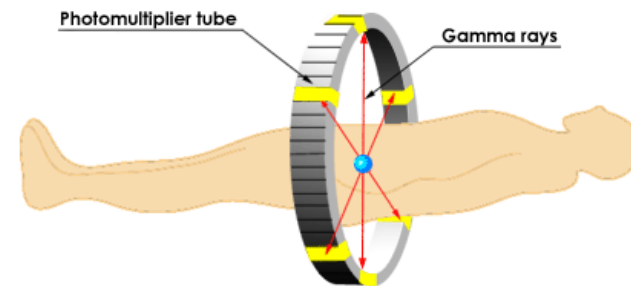
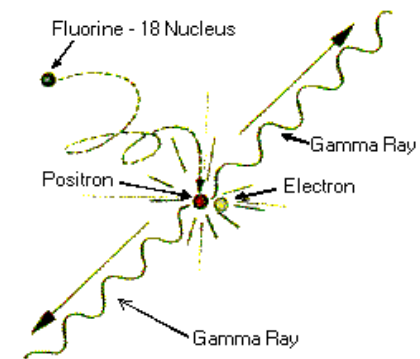
→ **distribution selon**

- métabolisme
- débit sanguin
- ligand (récepteurs, ex: DA)

- **SPECT: single photon emission CT**

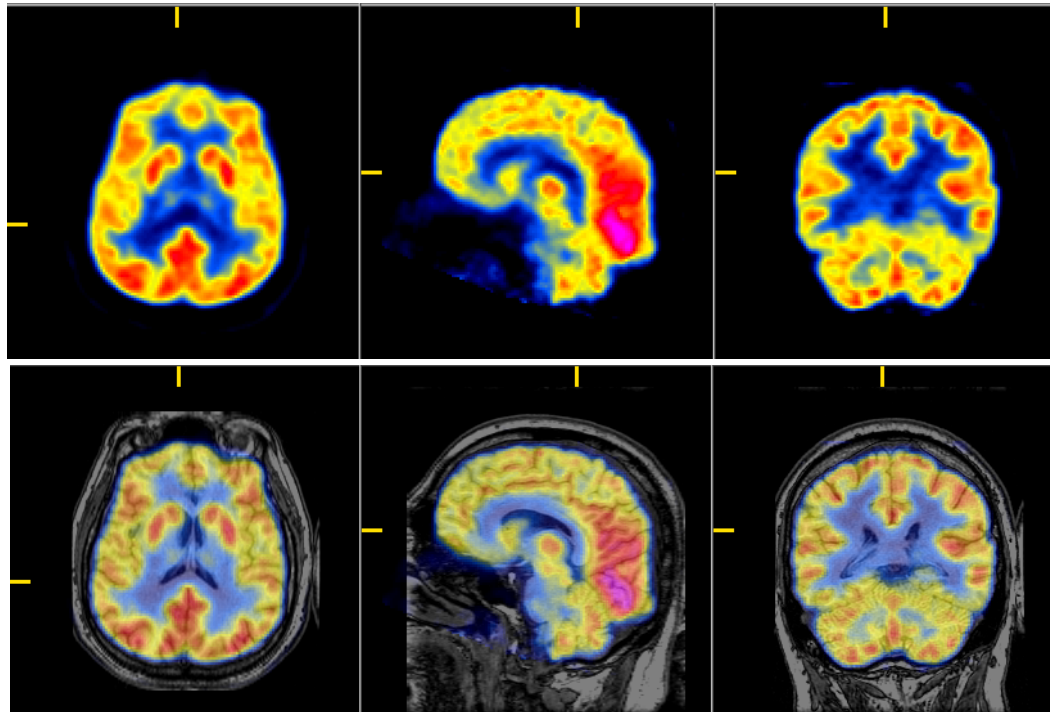
^{133}Xe , ^{123}I , $^{99\text{m}}\text{Tc}$

Positron Emission Tomography



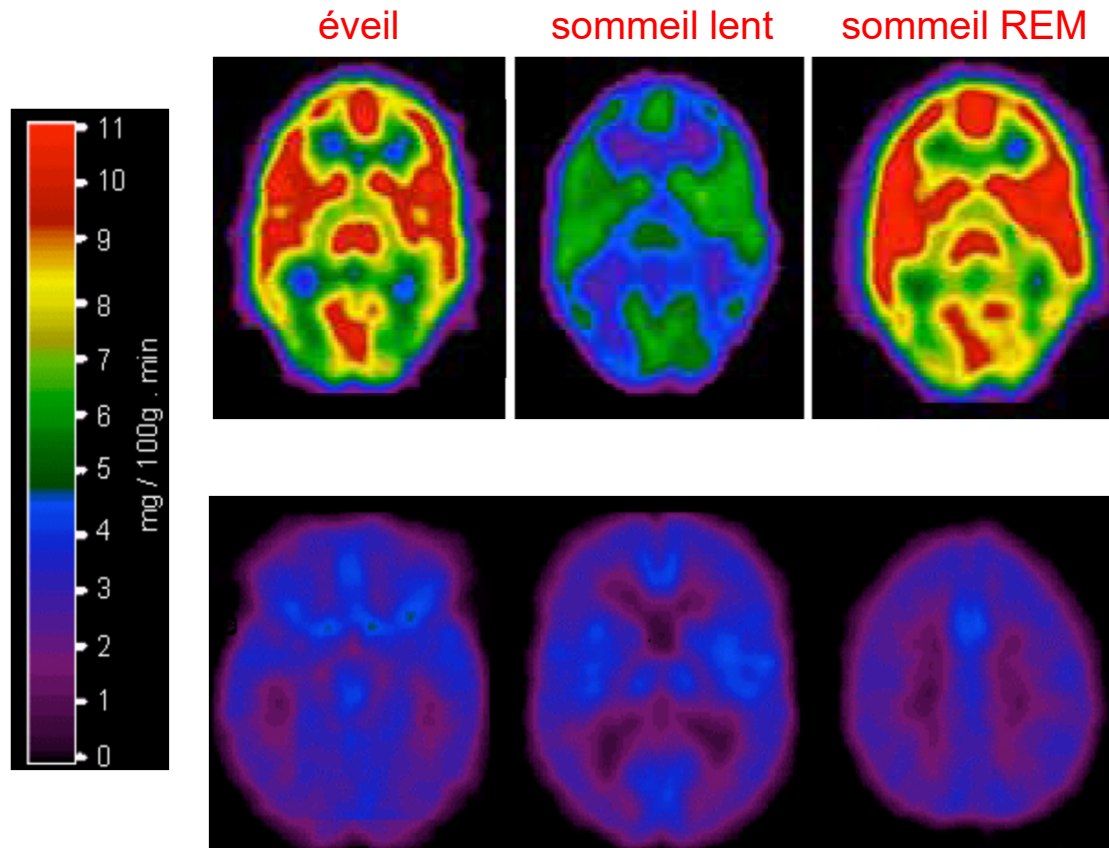
FDG-PET

+ IRM anat:



- NB:
- résolution PET ~4 mm, SPECT ~8 mm;
 - acquisition = plusieurs minutes
 - radioexposition = non répétable

FDG et éveil cortical



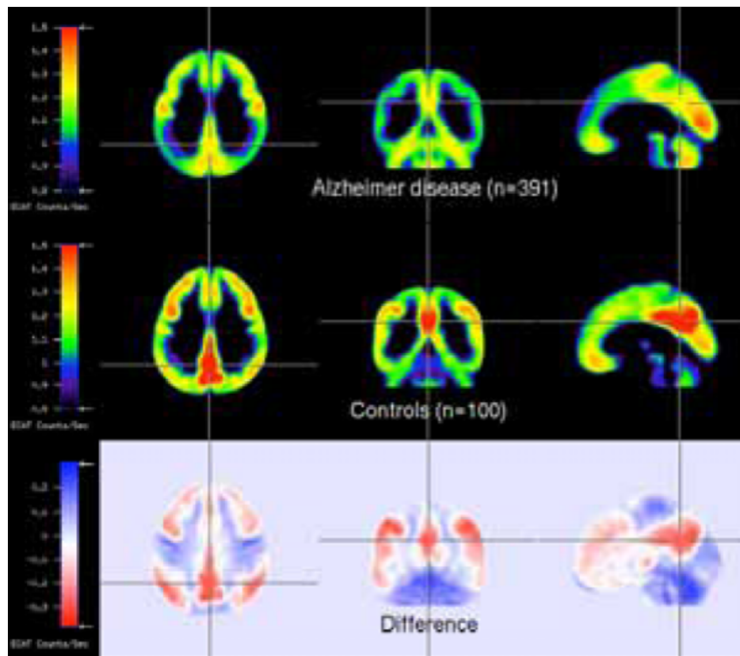
- Veille & Sommeil

- Coma: état végétatif

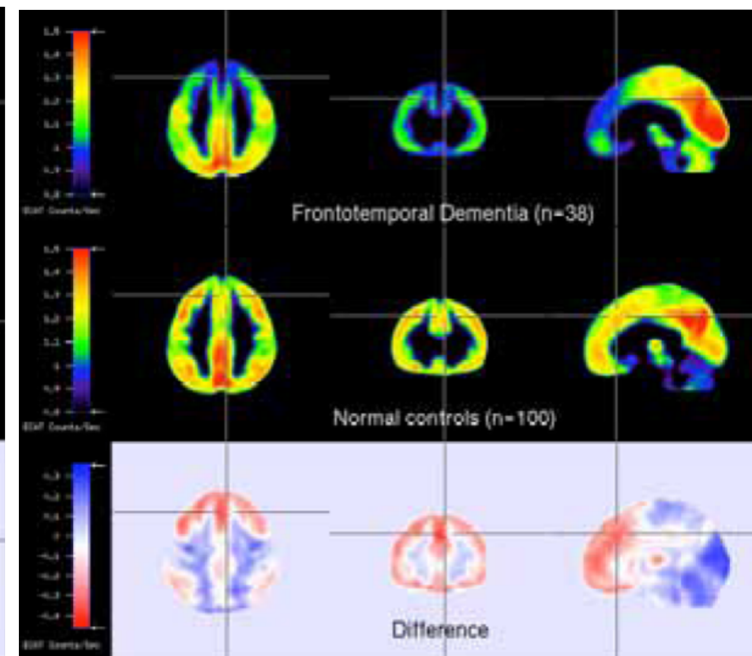
FDG & démences

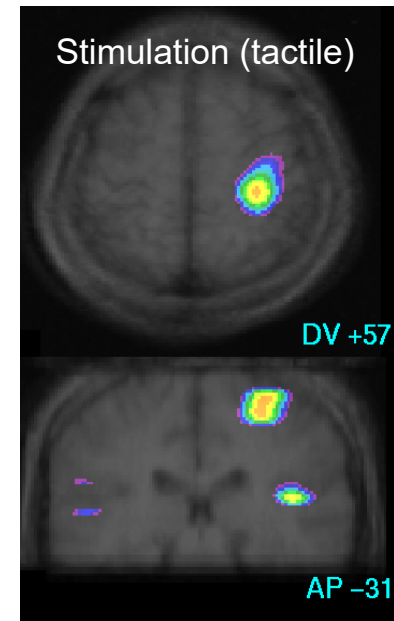
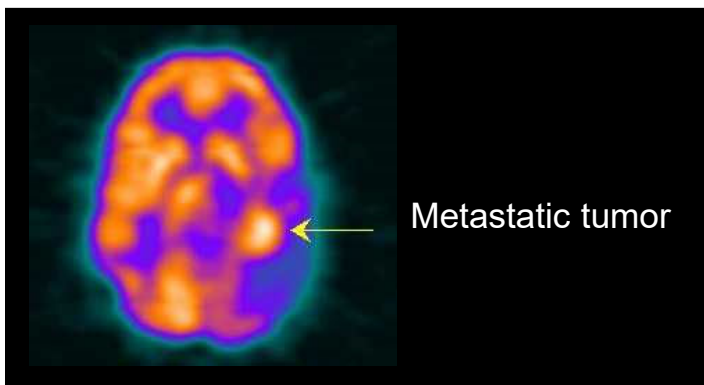
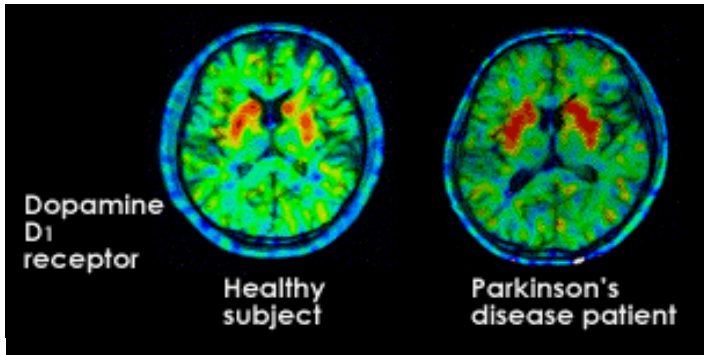
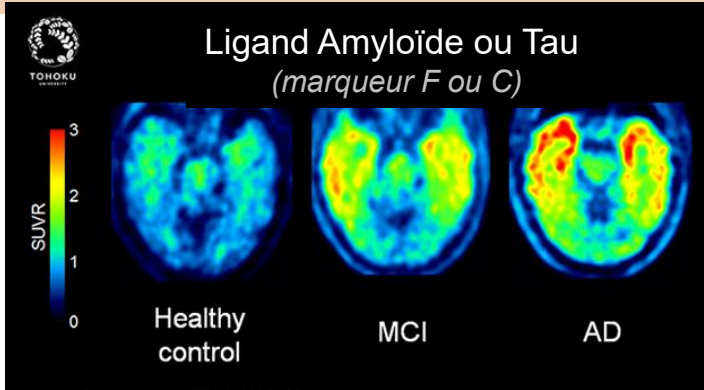


Alzheimer

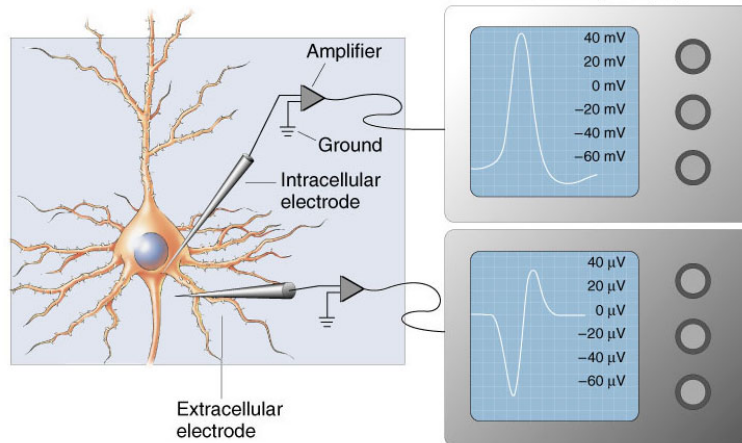


Démence frontale





Imagerie électrophysiologique



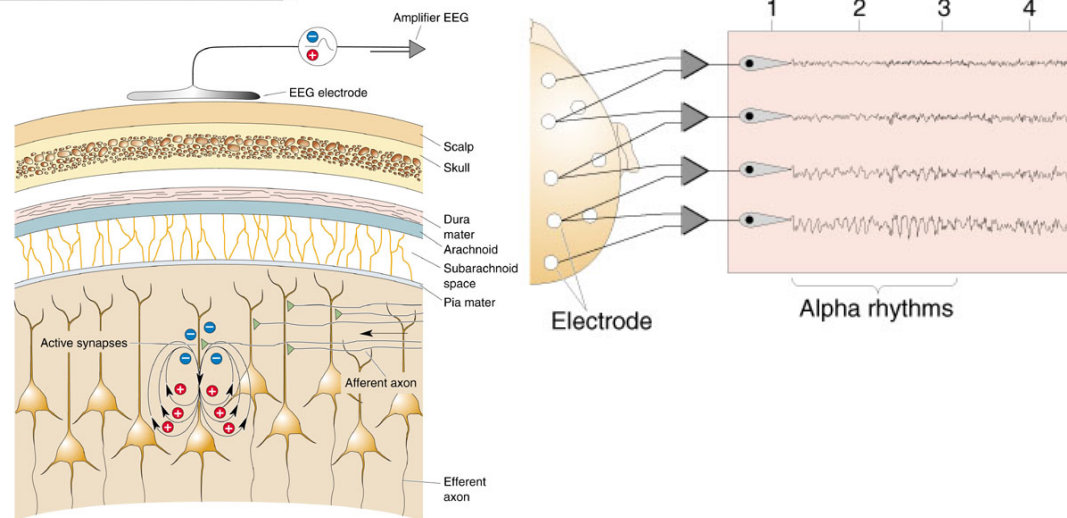
EEG: électro-encéphalographie
MEG: magnéto-encéphalographie



EEG

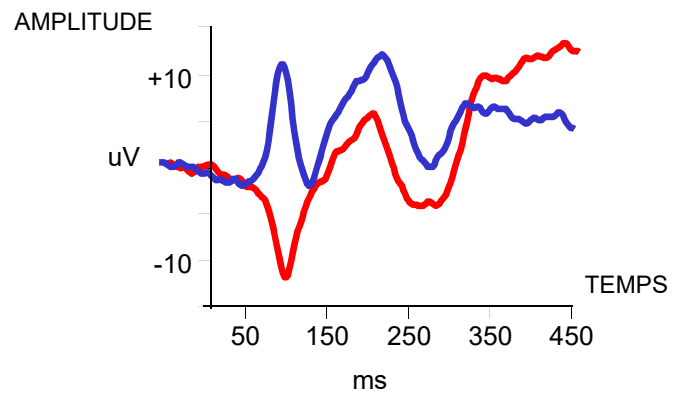


MEG

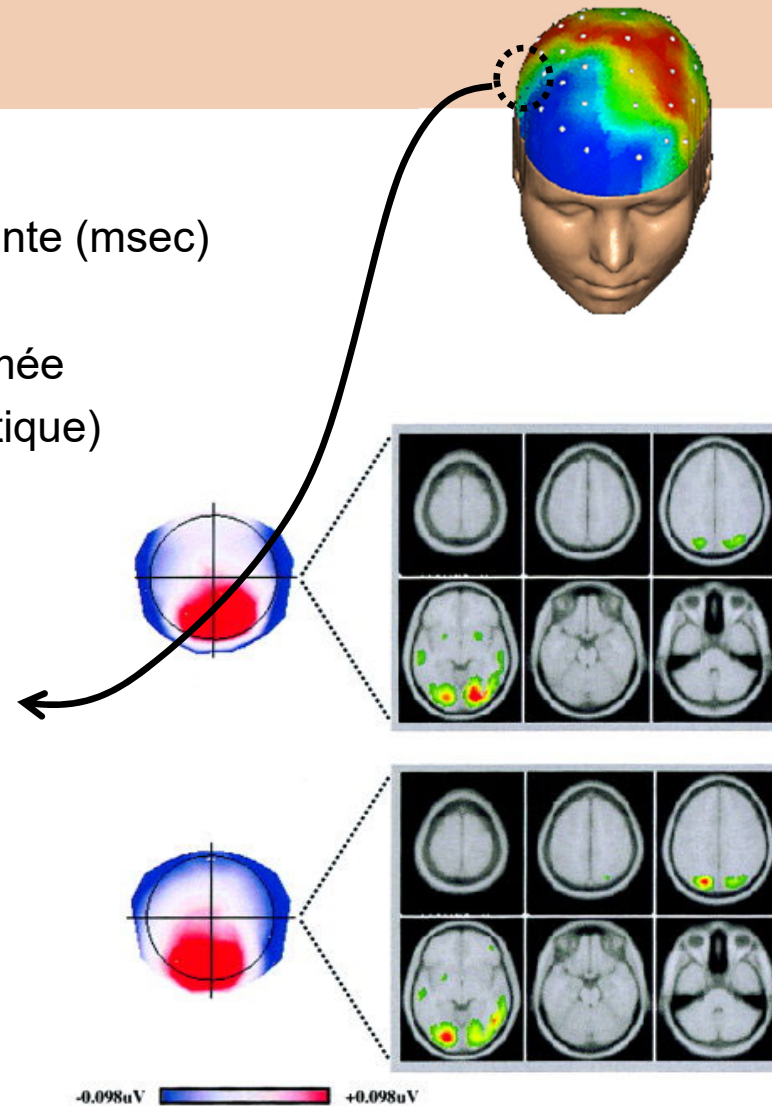


EEG

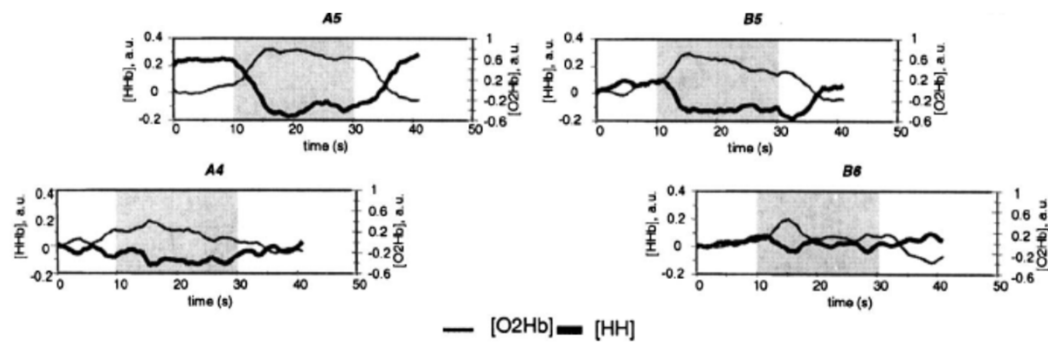
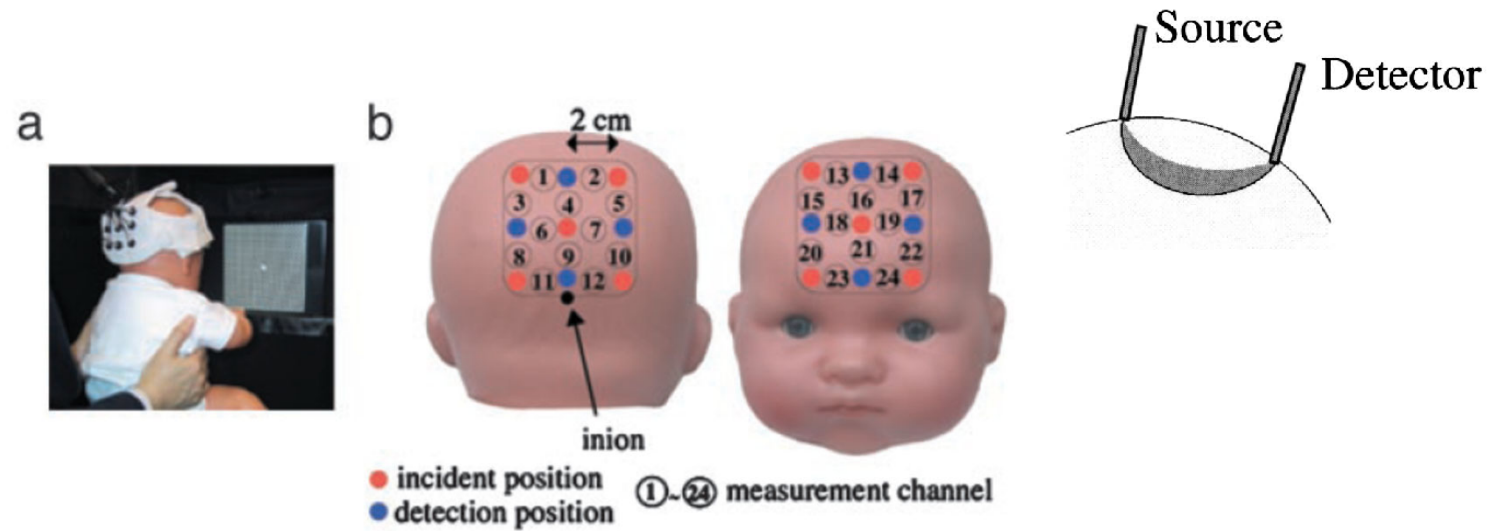
- résolution temporelle excellente (msec)
- résolution spatiale limitée
(source inconnue, mais estimée par reconstruction mathématique)



- Stimulation du champ visuel inférieur
- Stimulation du champ visuel supérieur



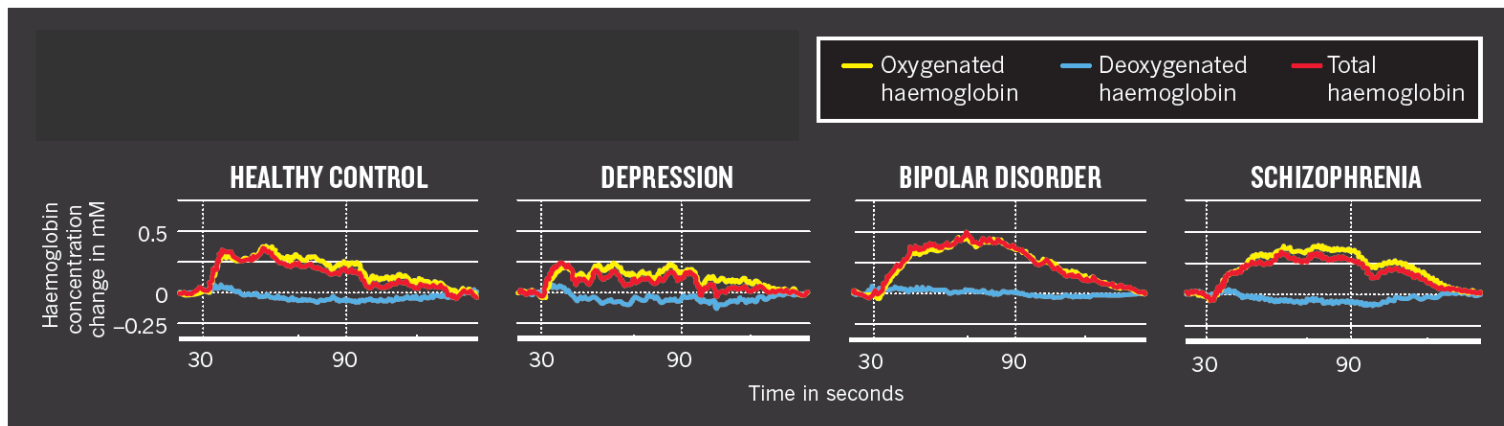
NIRS



NIRS



- Utilisation «portable»
- Emploi pour diagnostic psychiatrique?
(e.g. Japon)
- Ex: activité frontale au cours de 60 secs
de tâche cognitive



En résumé:



- Complexité anatomique et fonctionnelle du SNC
- Diversité et complémentarité des techniques de neuroimagerie (peu ou non-invasives)
- Importance de l'imagerie multi-modale:
 - compréhension du cerveau normal "in vivo", cognition
 - développement, vieillissement
 - diagnostic neurologique, bilan pré/post neurochirurgical
 - effets thérapeutiques, pharmacologiques
 - maladies psychiatriques
 - génétique, différences individuelles ...

Références



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- “Functional MRI: Basic Principles and Clinical Applications”
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- “Brain Mapping: An Encyclopedic Reference”
A. Toga (ed).
(Academic Press/Elsevier, 2015)
- “Brain network dysfunction in neuropsychiatric illness”
V.A. Diwadkar & S.B. Eickhoff
(Springer Nature, 2021)
- “Challenges and opportunities for advancing functional MRI in clinical practice”
N.L. Voets et coll.
(Brain 2025, Vol 148:7, pages 2242–2246)