

Etude morphométrique du développement cérébral in utero à partir d'IRM

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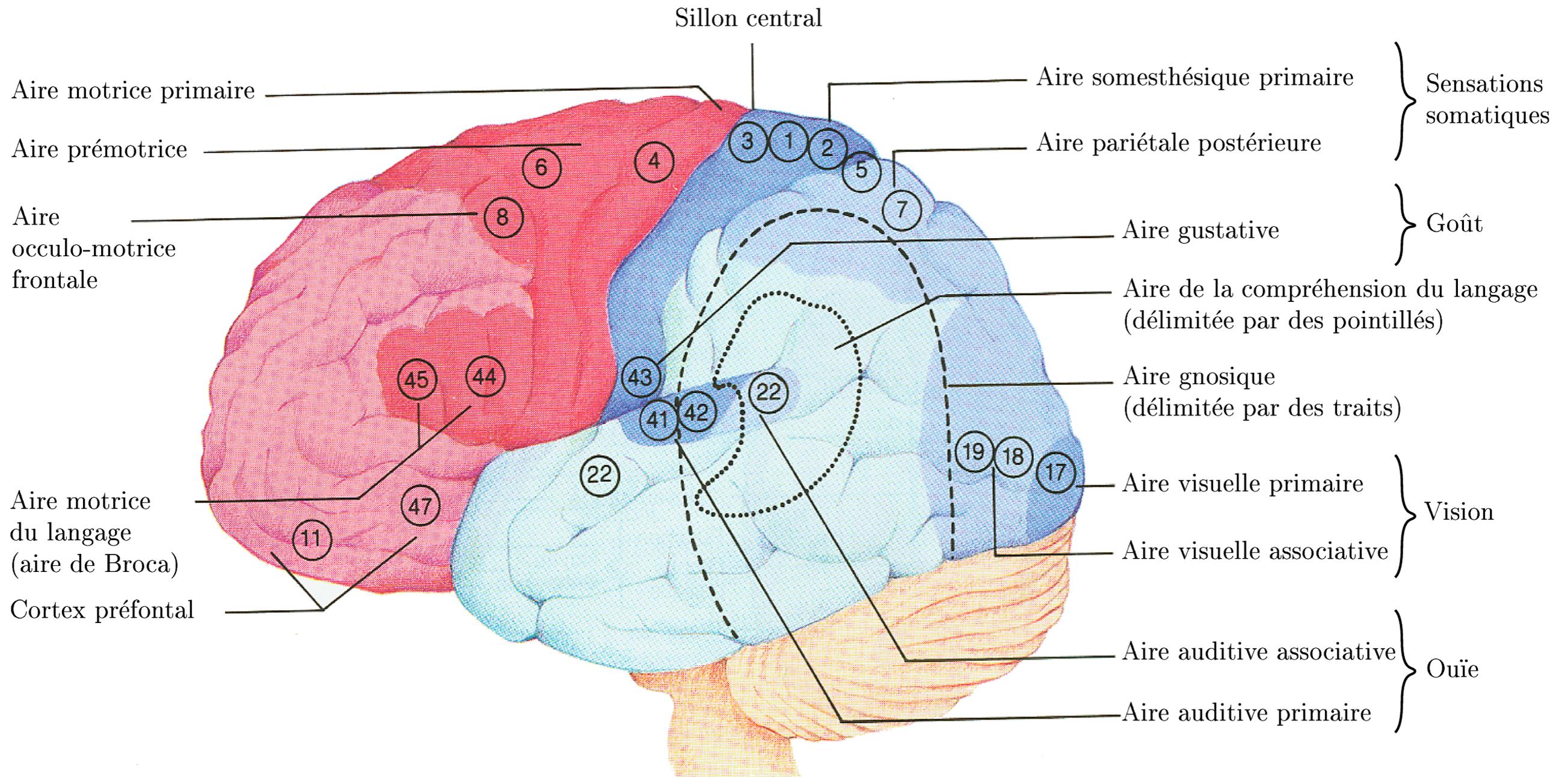


Cartographie du cerveau

fonctions et structures

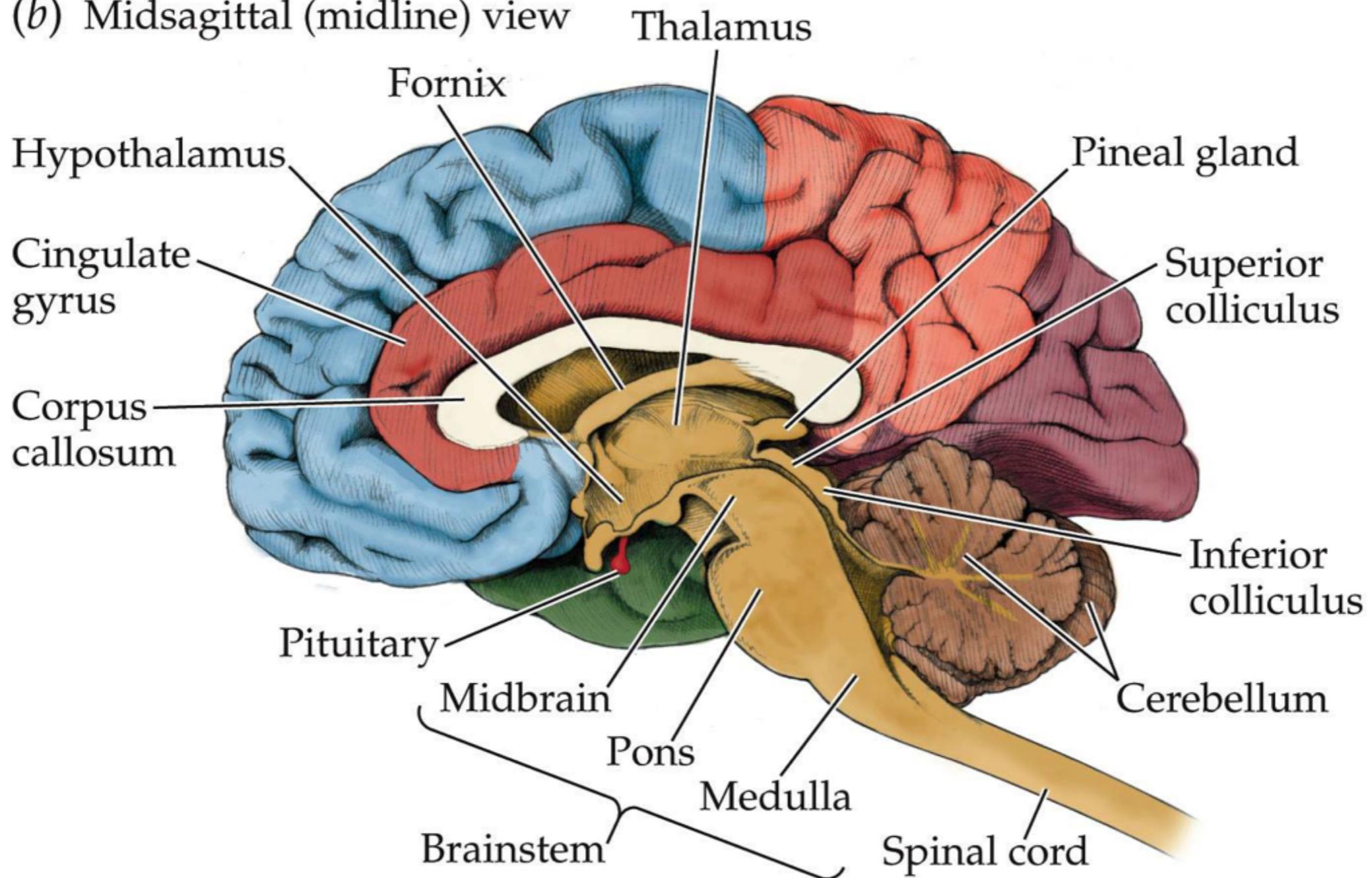


Fonctions



Structures

(b) Midsagittal (midline) view



IRM(a,s,d,f)

TEP

MEG/EEG

histologie

etc.

spectre chimique

myéline

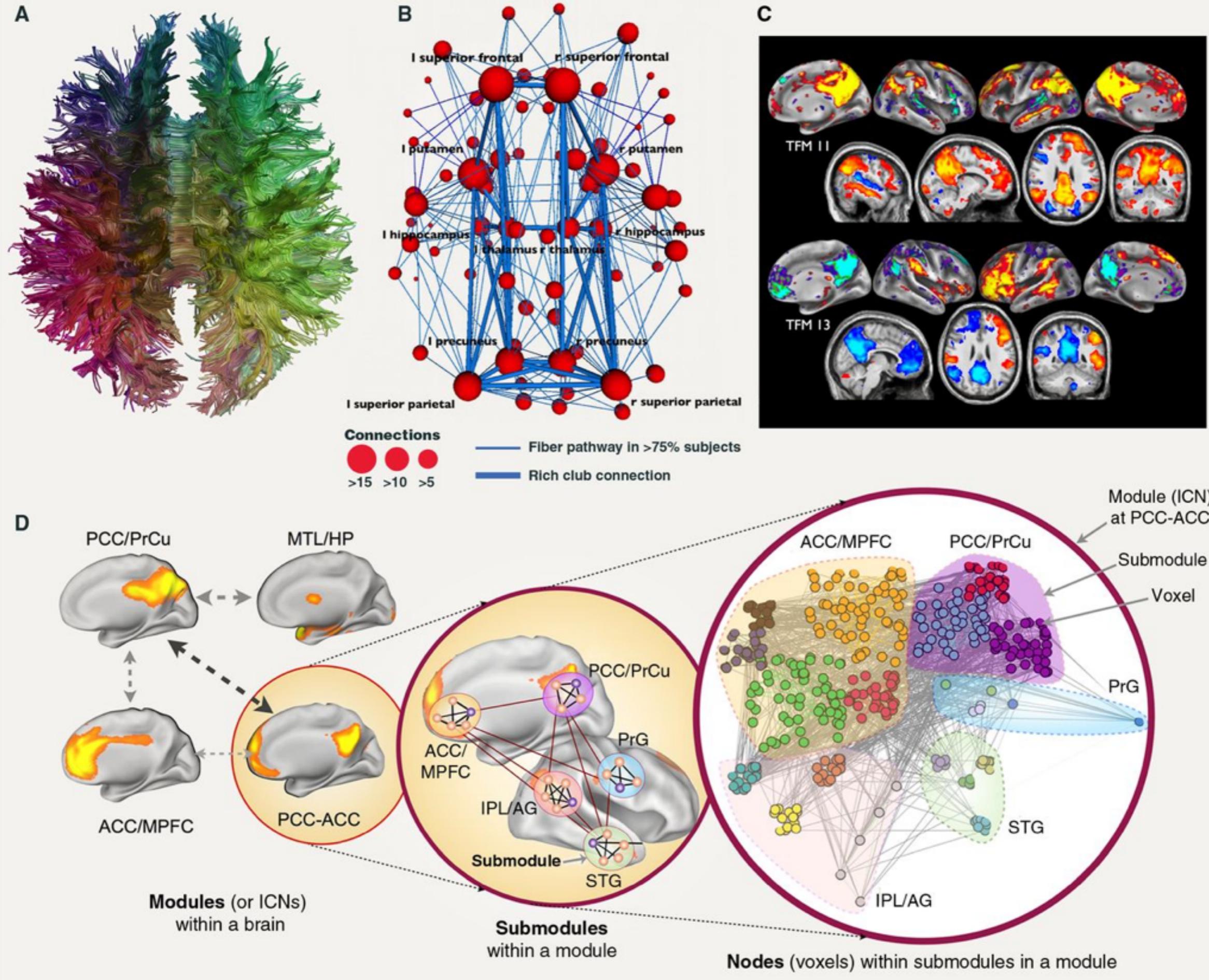
densité de protéines

ARNm

«cablâge»

«activité»

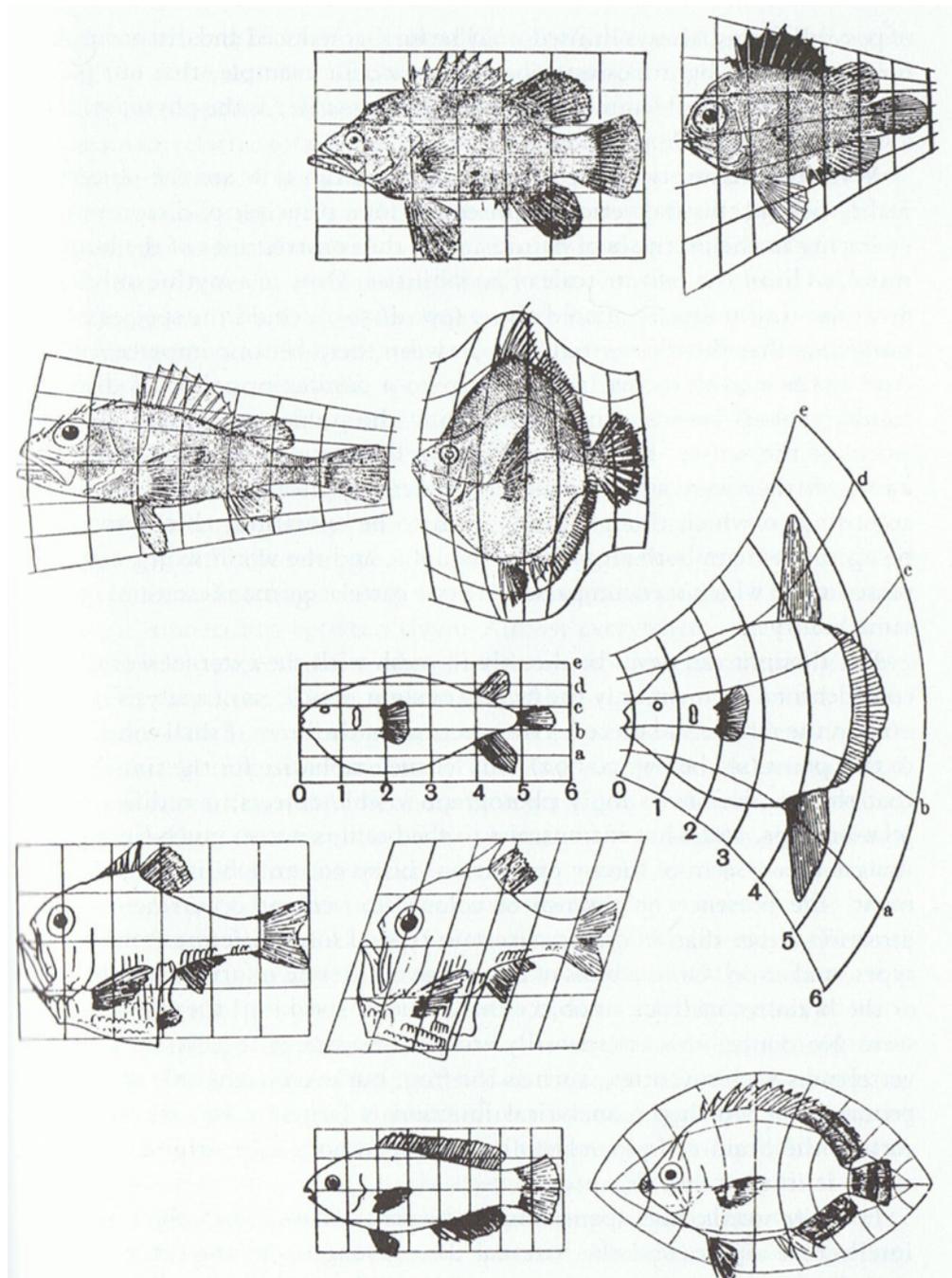
etc.



[Park & Friston 2013]

Morphométrie

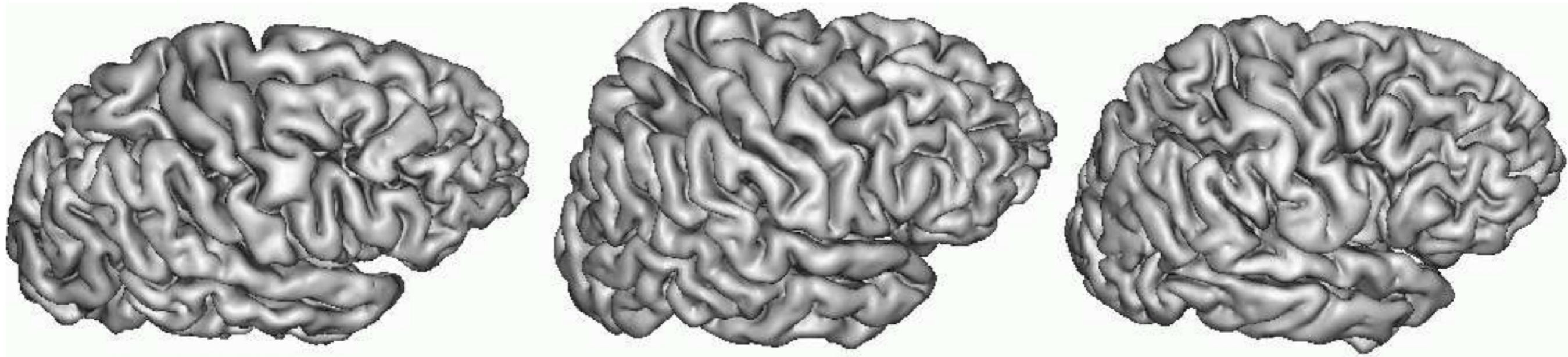
La morphométrie est
l'étude et l'analyse de
la géométrie d'objets.



La morphométrie est l'étude et l'analyse de la géométrie d'objets.

[D'Arcy Thompson 1917]

Complexité et variabilité



Pourquoi faire ?

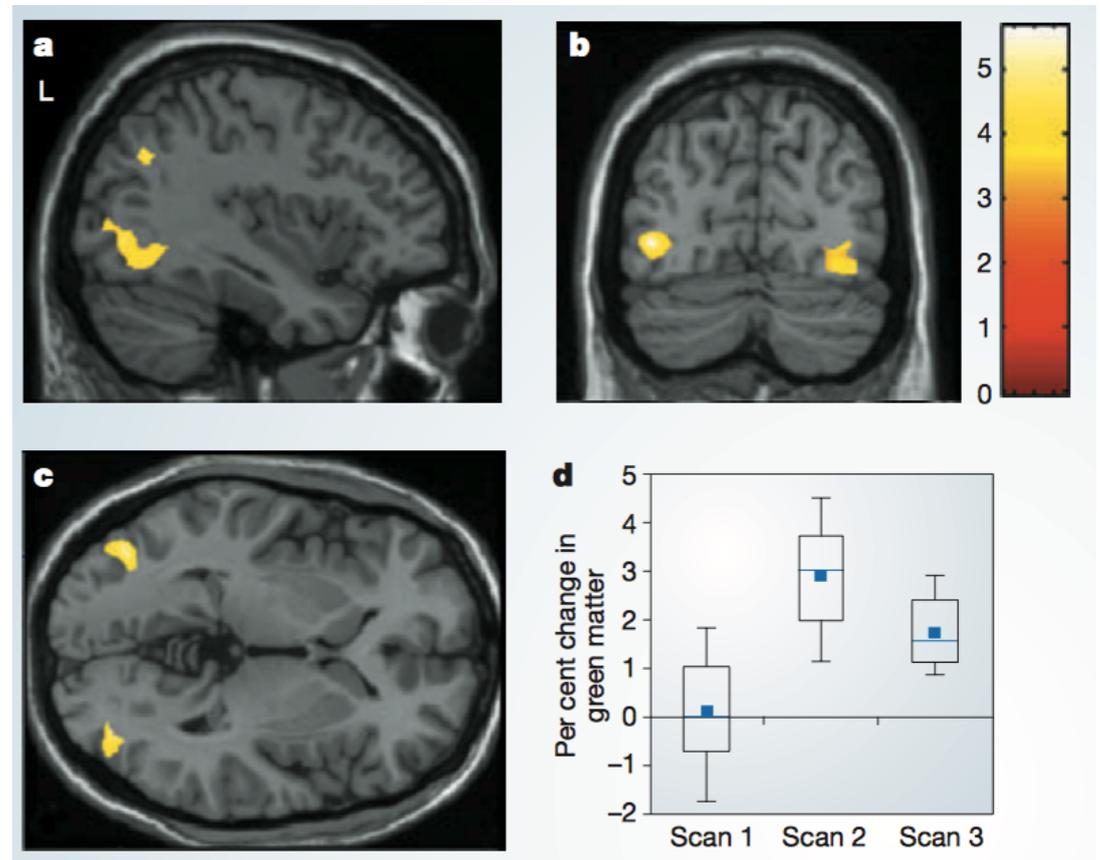
- Quelles régions s'atrophient avec l'âge ?
- Comment le cerveau se ré-organise lors de l'apprentissage de nouvelles tâches ?
- Comment le cerveau se développe-t-il ?

Plasticité cérébrale

Comment le cerveau se ré-organise
lors de l'apprentissage de nouvelles tâches ?

24 sujets ne sachant pas jongler
12 sujets effectuent un apprentissage

Augmentation significative
de la substance grise
chez les jongleurs

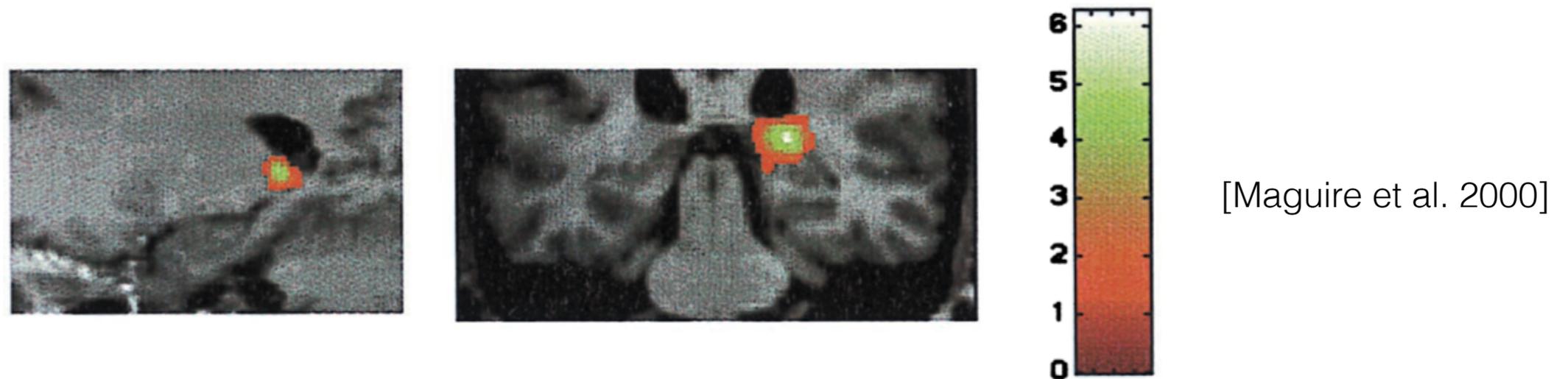


[Draganski et al. 2004]

Mémoire spatiale

Est-ce que les personnes ayant une très bonne mémoire spatiale ont une anatomie cérébrale différente des autres?

16 chauffeurs de taxi vs 50 contrôles



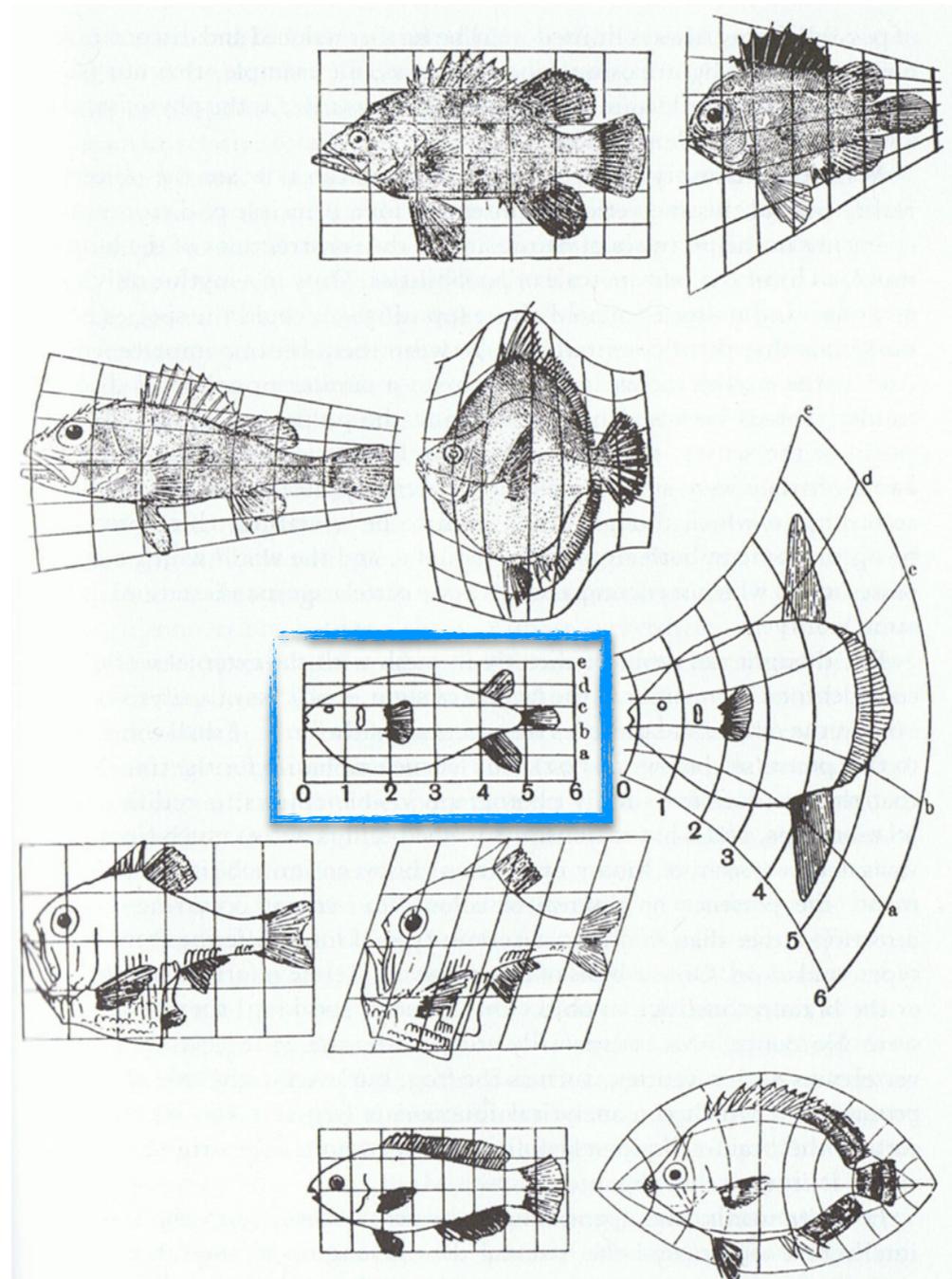
Augmentation significative de la substance grise dans l'hippocampe des chauffeurs de taxi & corrélation positive avec l'expérience de conduite

Comment faire ?

3 ingrédients

unité de mesure	un repère (cerveau modèle)
définir une façon de comparer	mise en correspondance
quantifier les différences	opérations sur les transformations

Les repères

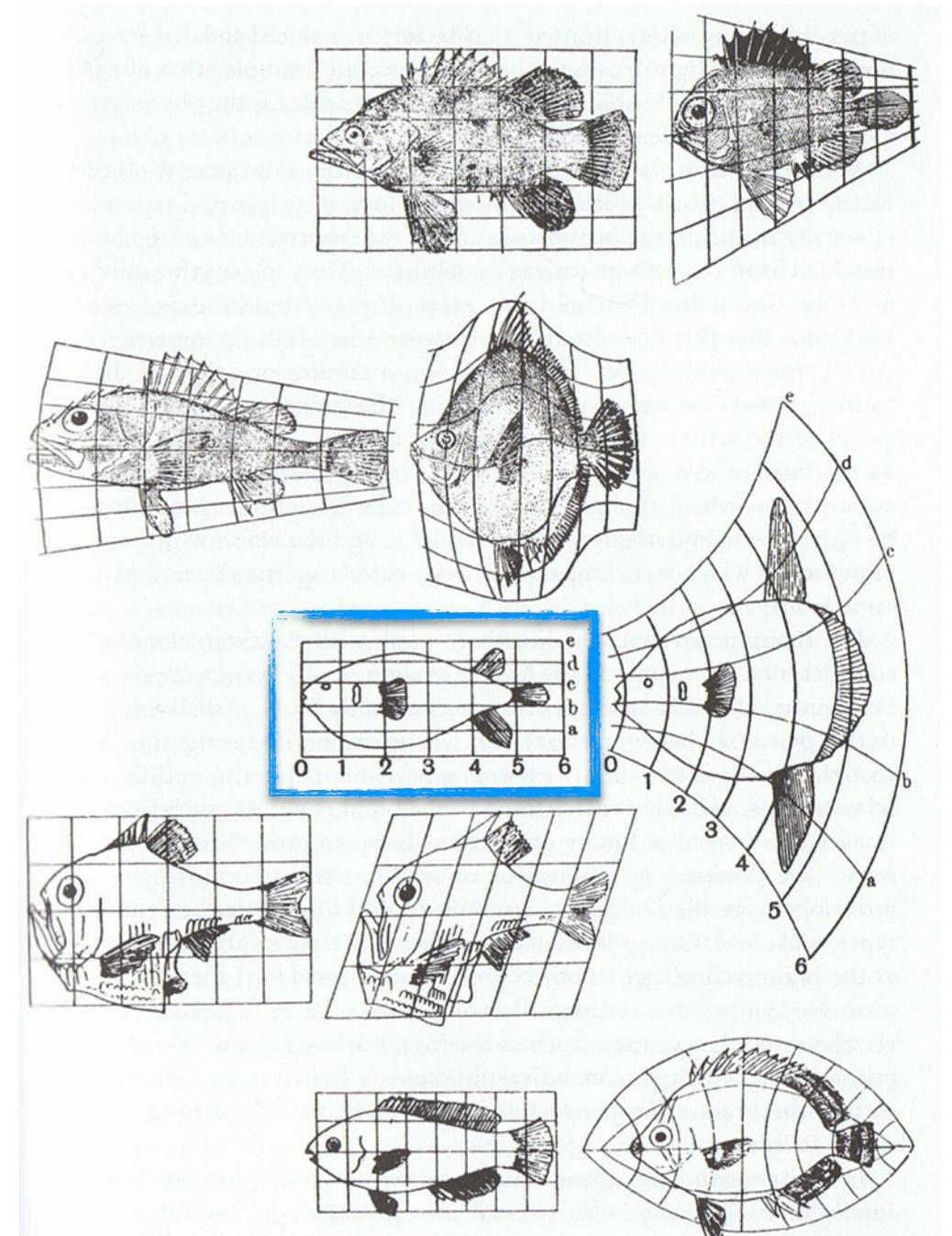


[D'Arcy Thompson 1917]

Situer une région

Calculer sa forme, ses caractéristiques

Calculer des différences par rapport à une référence

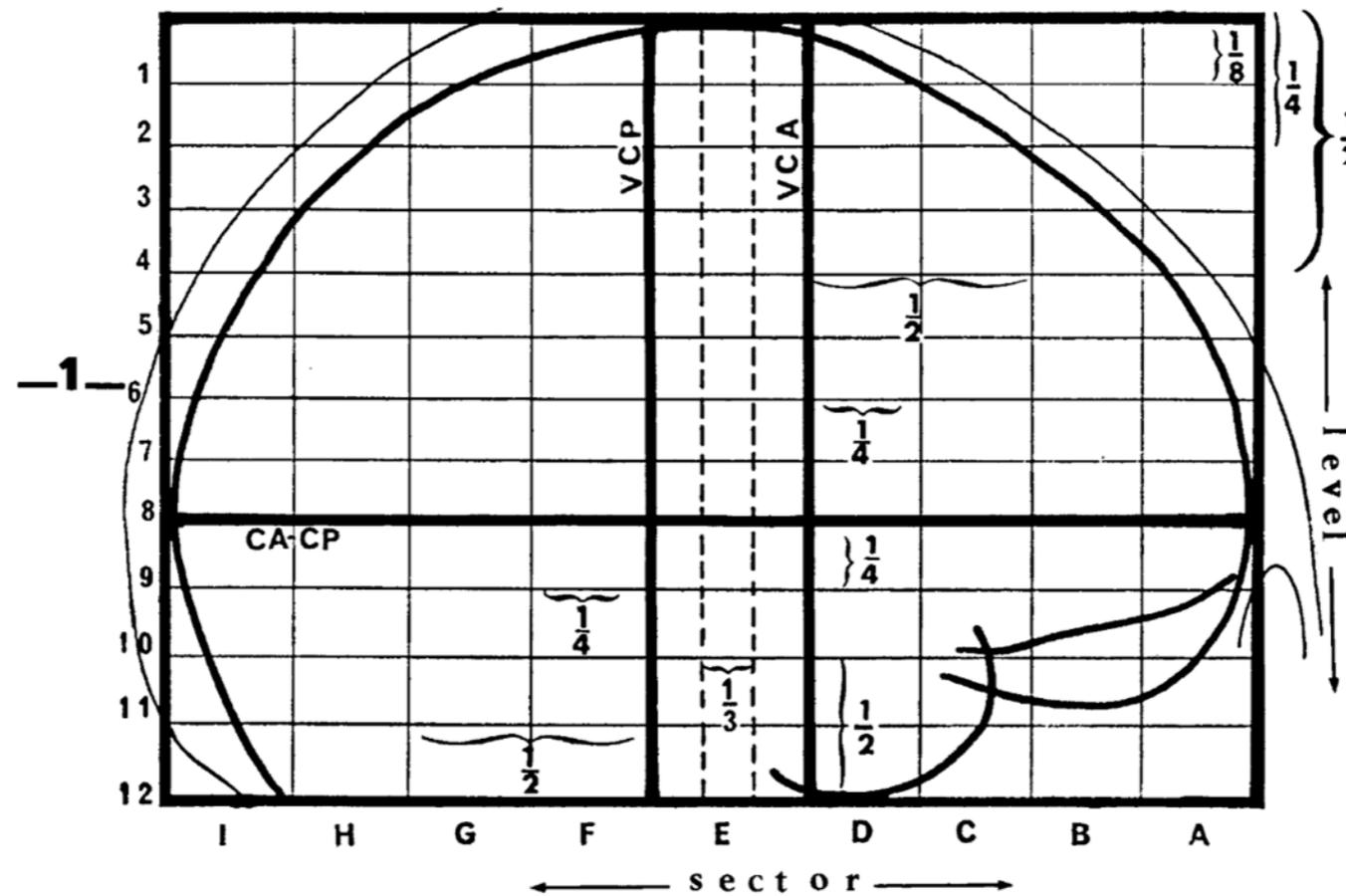


[D'Arcy Thompson 1917]

Atlas de Talairach

- «A **standard brain space** is needed for consistent spatial localization in both individual and composite images, and this is provided by the **Talairach space**.»
- «low degree-of-freedom regional method»

Atlas de Talairach

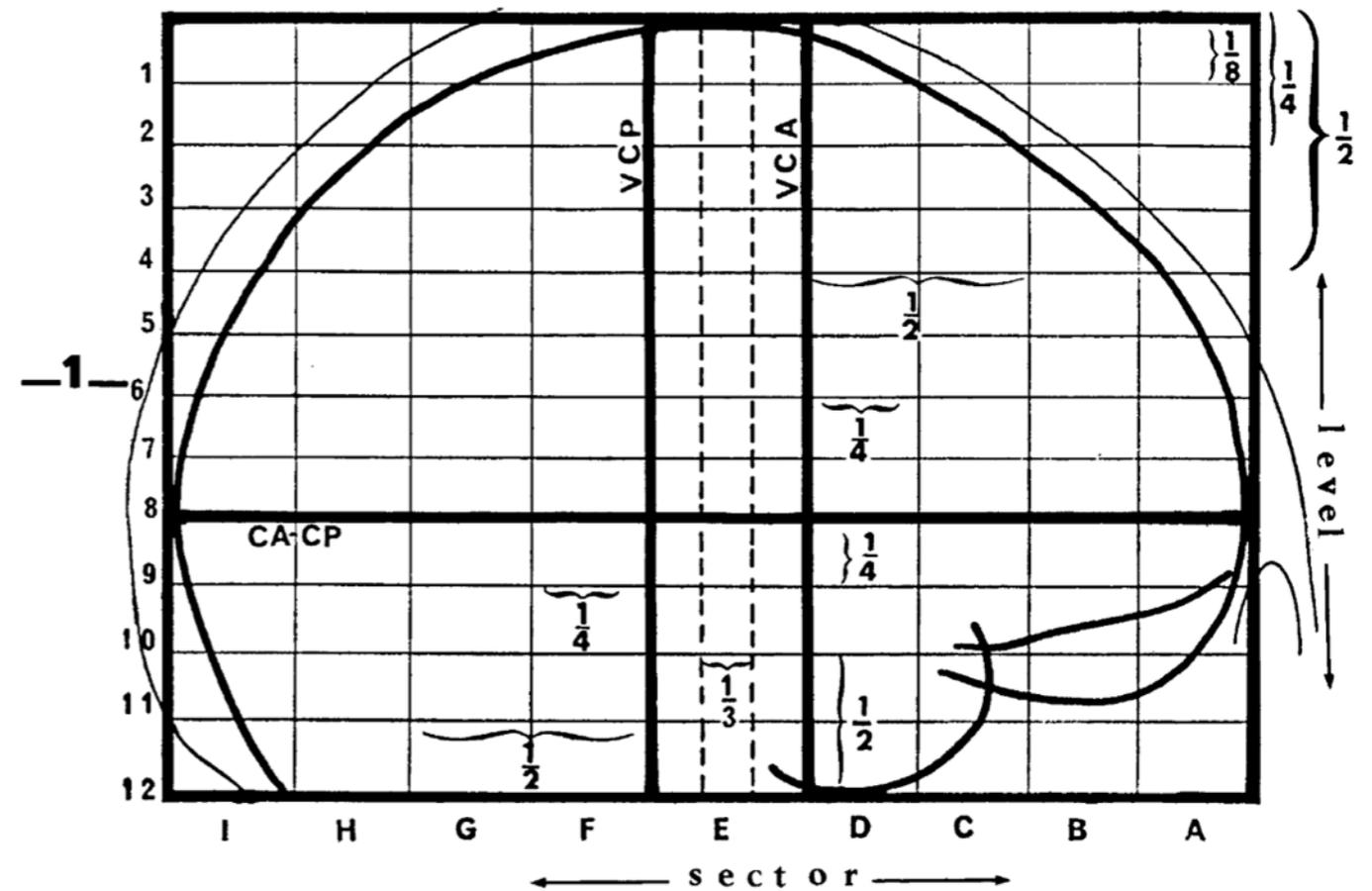


Atlas de Talairach

repère 3D orienté

déformations linéaires
par morceaux

atlas anatomique



- une seule image de référence ne peut représenter la variabilité structurelle
- la variabilité est encodée dans les champs de déformations
- le choix de la référence introduit un biais
- une image moyenne peut être calculée pour une population donnée

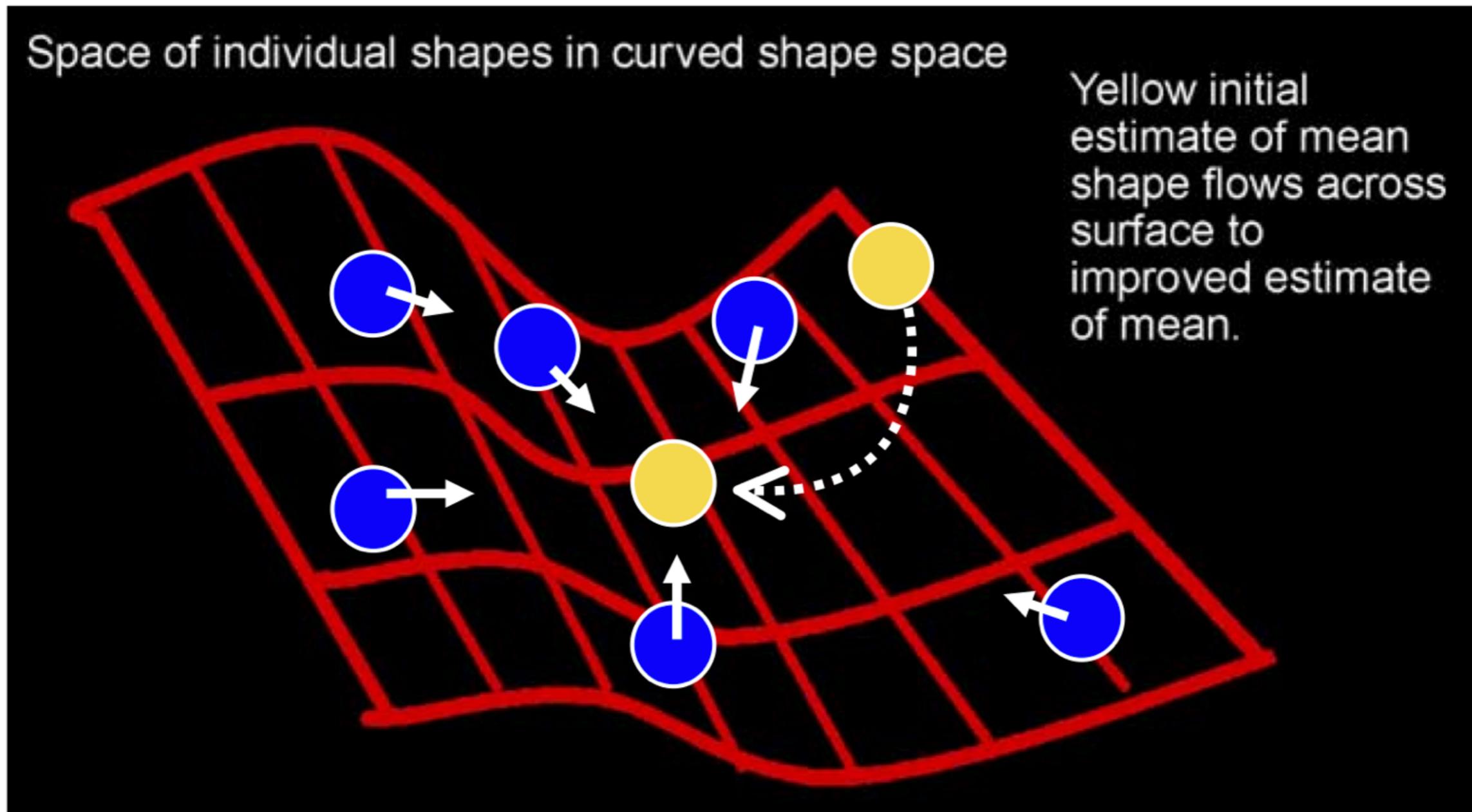
moyenne dans un espace vectoriel

$$\mu = \frac{1}{N} \sum_{i=1}^N x_i$$

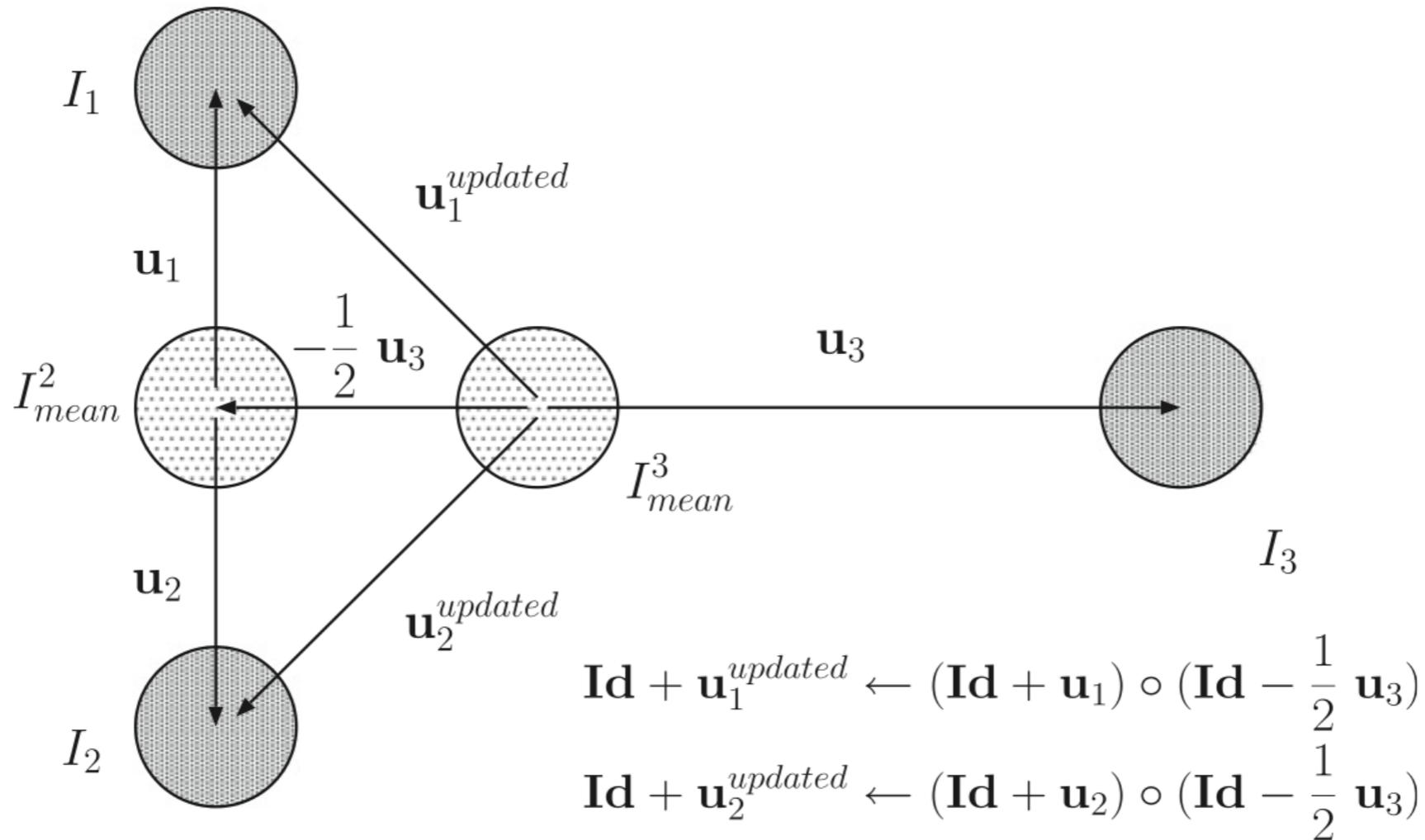
moyenne de Fréchet dans un espace métrique M

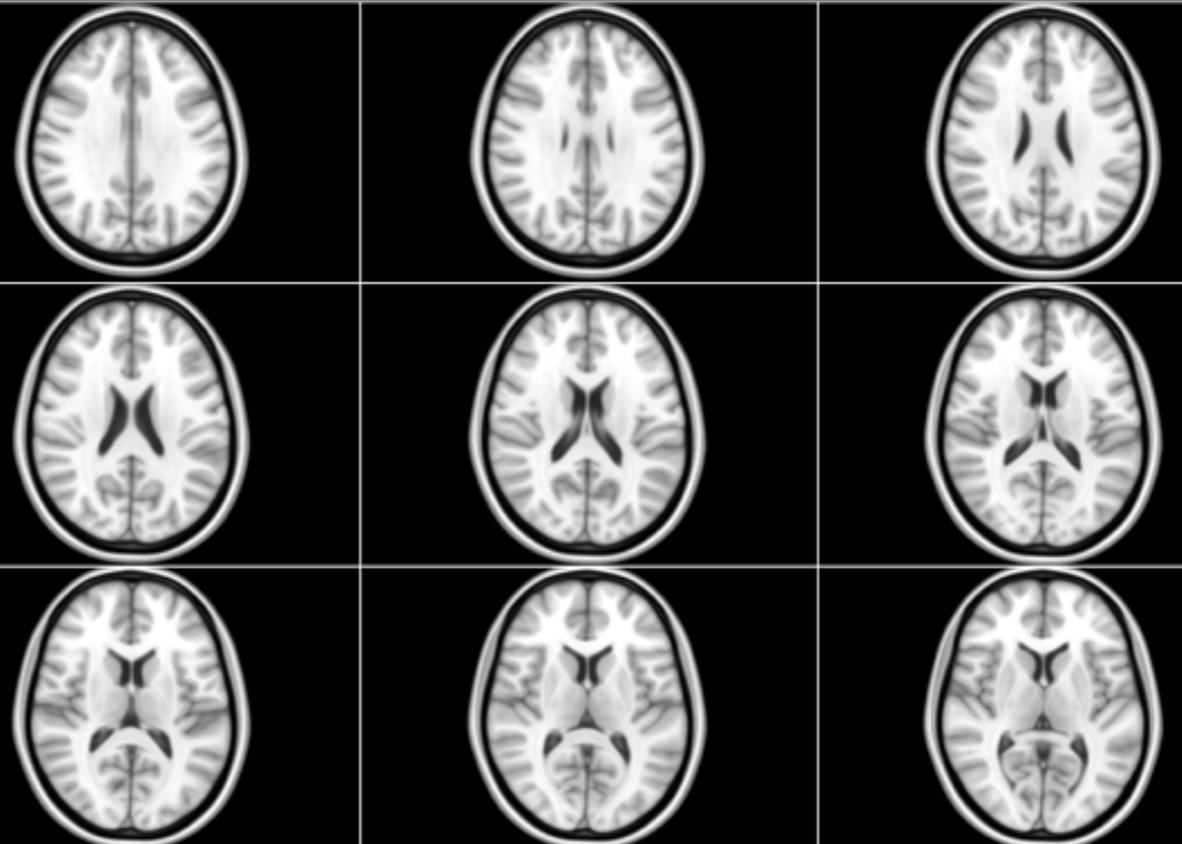
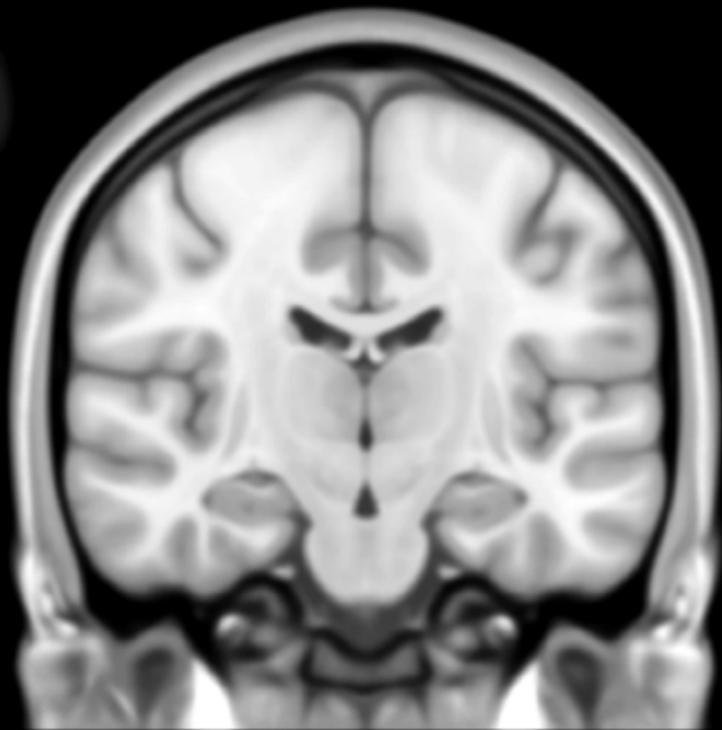
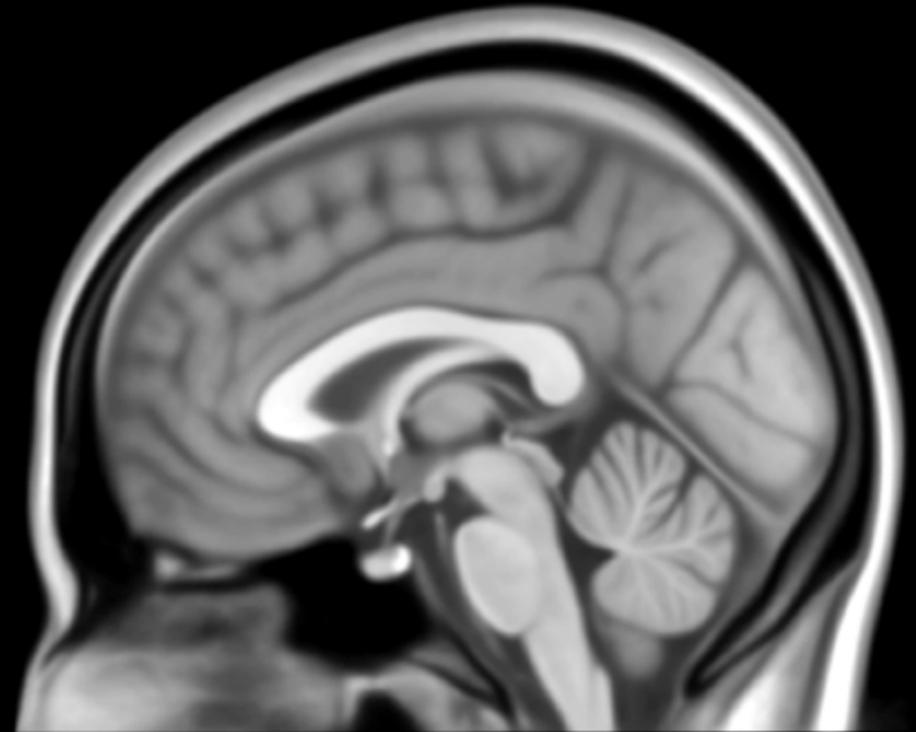
$$\mu = \arg \min_{x \in M} \sum_{i=1}^N d(x, x_i)^2$$

Estimation d'une image moyenne

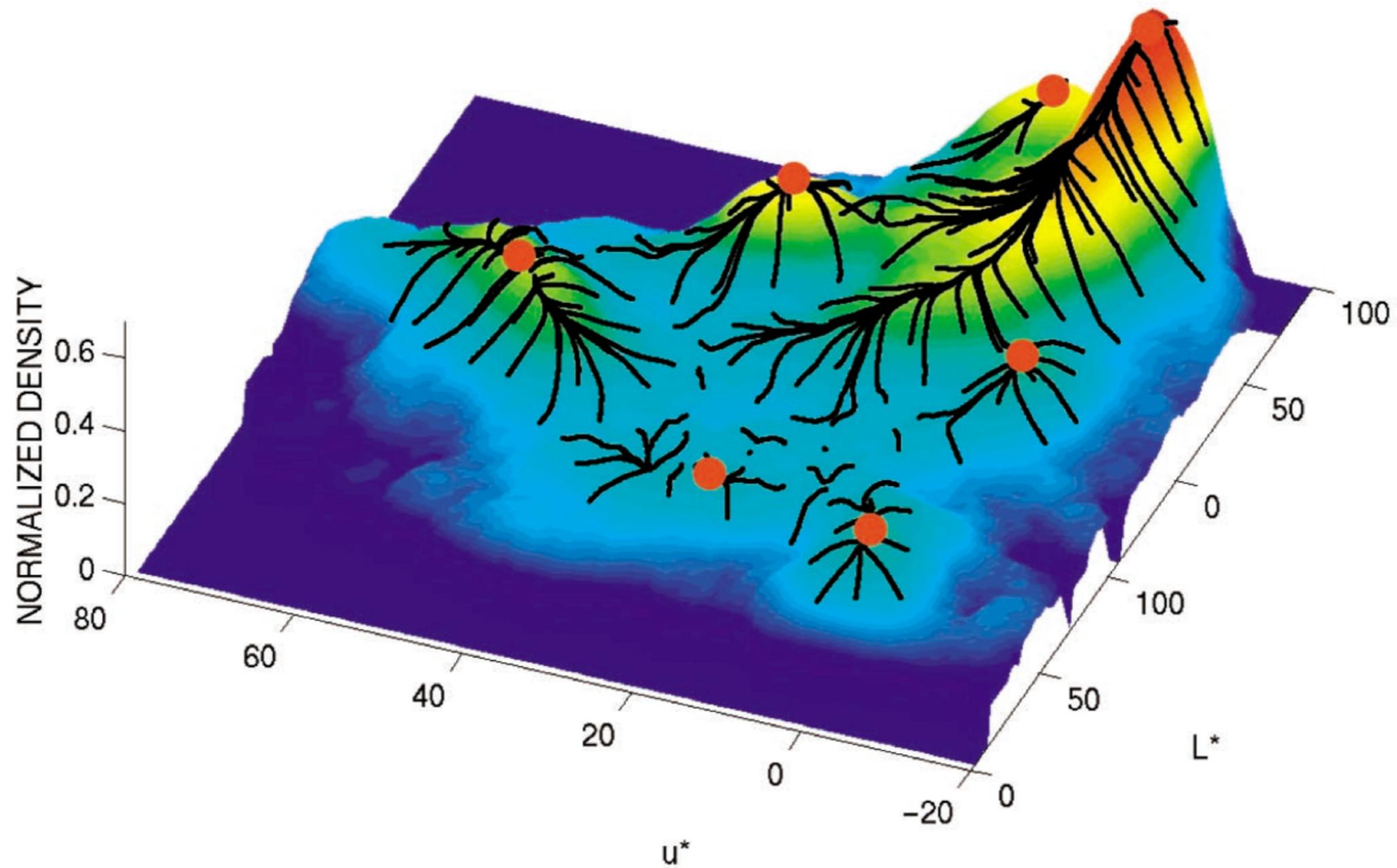


Estimation d'une image moyenne

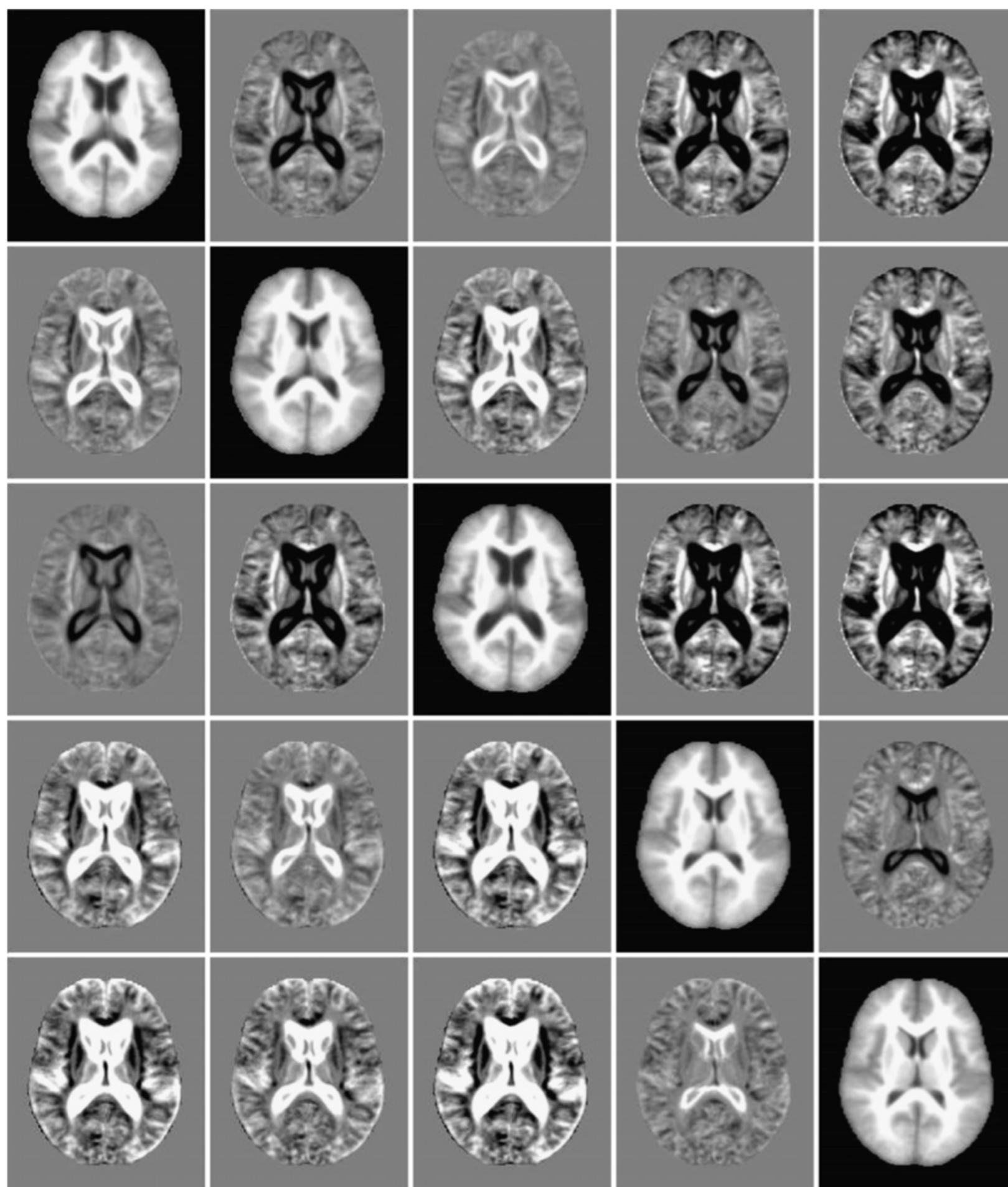




Approche non paramétrique



«mean shift», [Comaniciu et al. 2002]



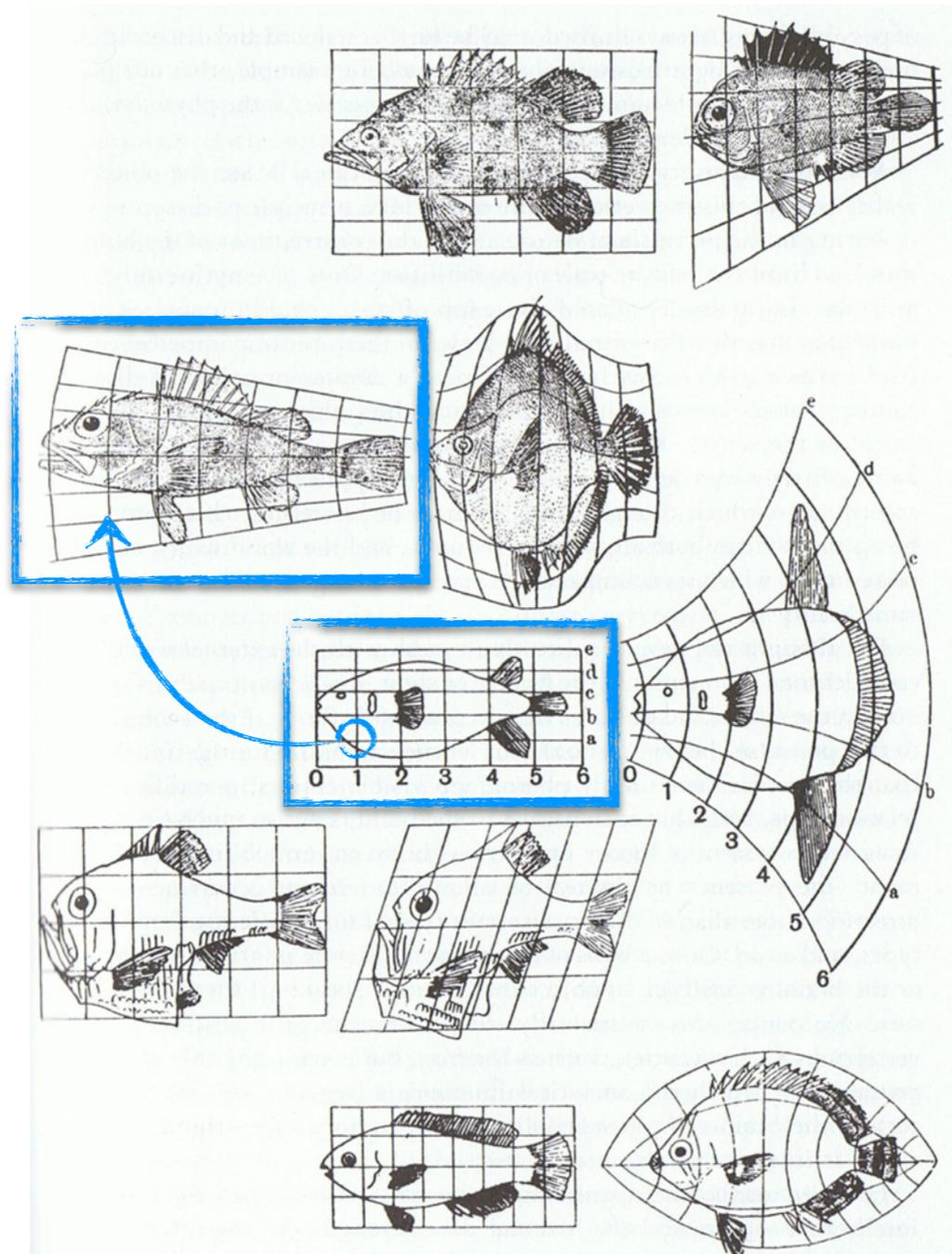
[Blezek et al. 2007]

L'objectif de l'étude fixe le choix de l'atlas.

«Accurate and representative atlases of the brain hold the most promise for helping to create a comprehensive understanding of the brain in health and disease.»

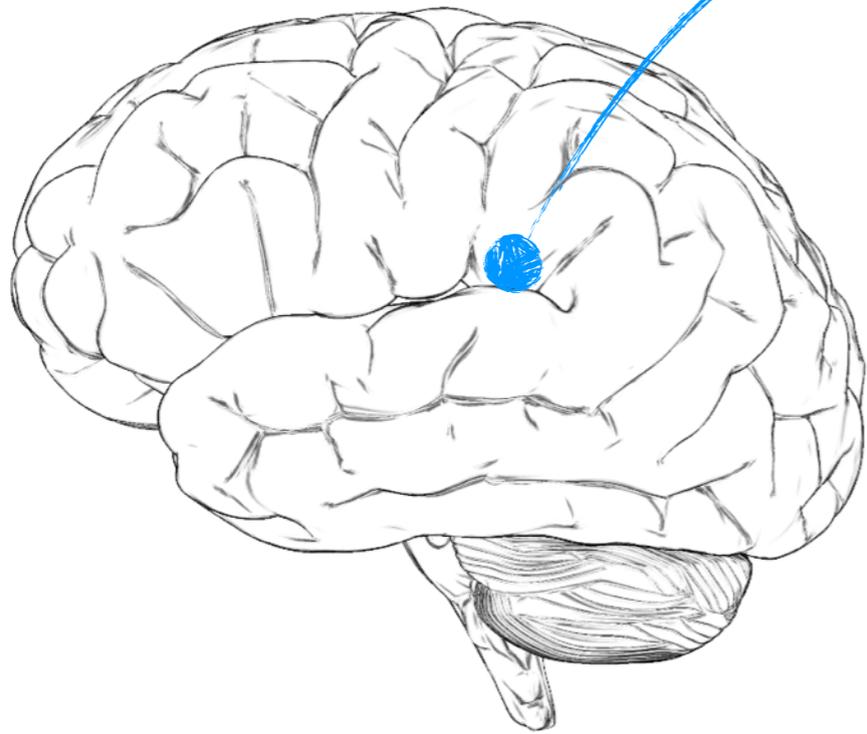
[Toga&Thompson 2008]

Mise en
correspondance

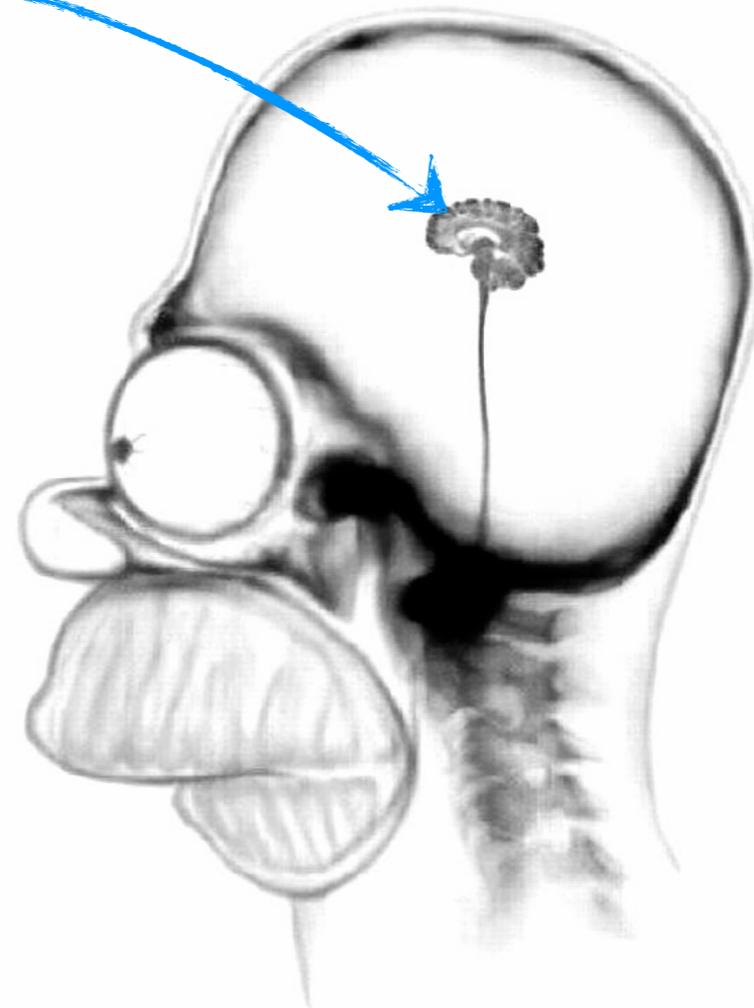


[D'Arcy Thompson 1917]

$$\mathbf{x}' = T(\mathbf{x})$$



$$\mathbf{x} = (x, y, z)$$

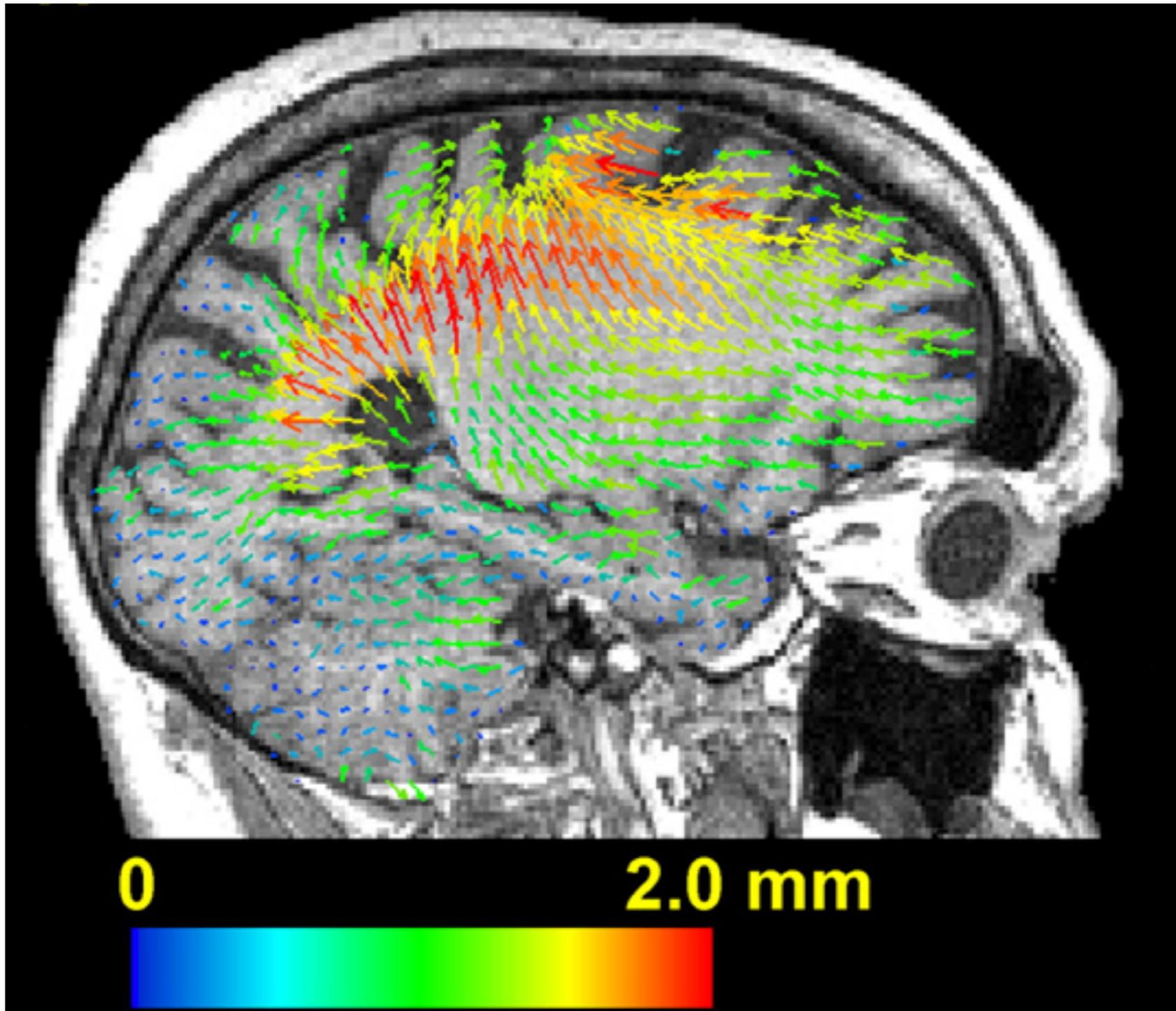


$$\mathbf{x}' = (x', y', z')$$

Le recalage

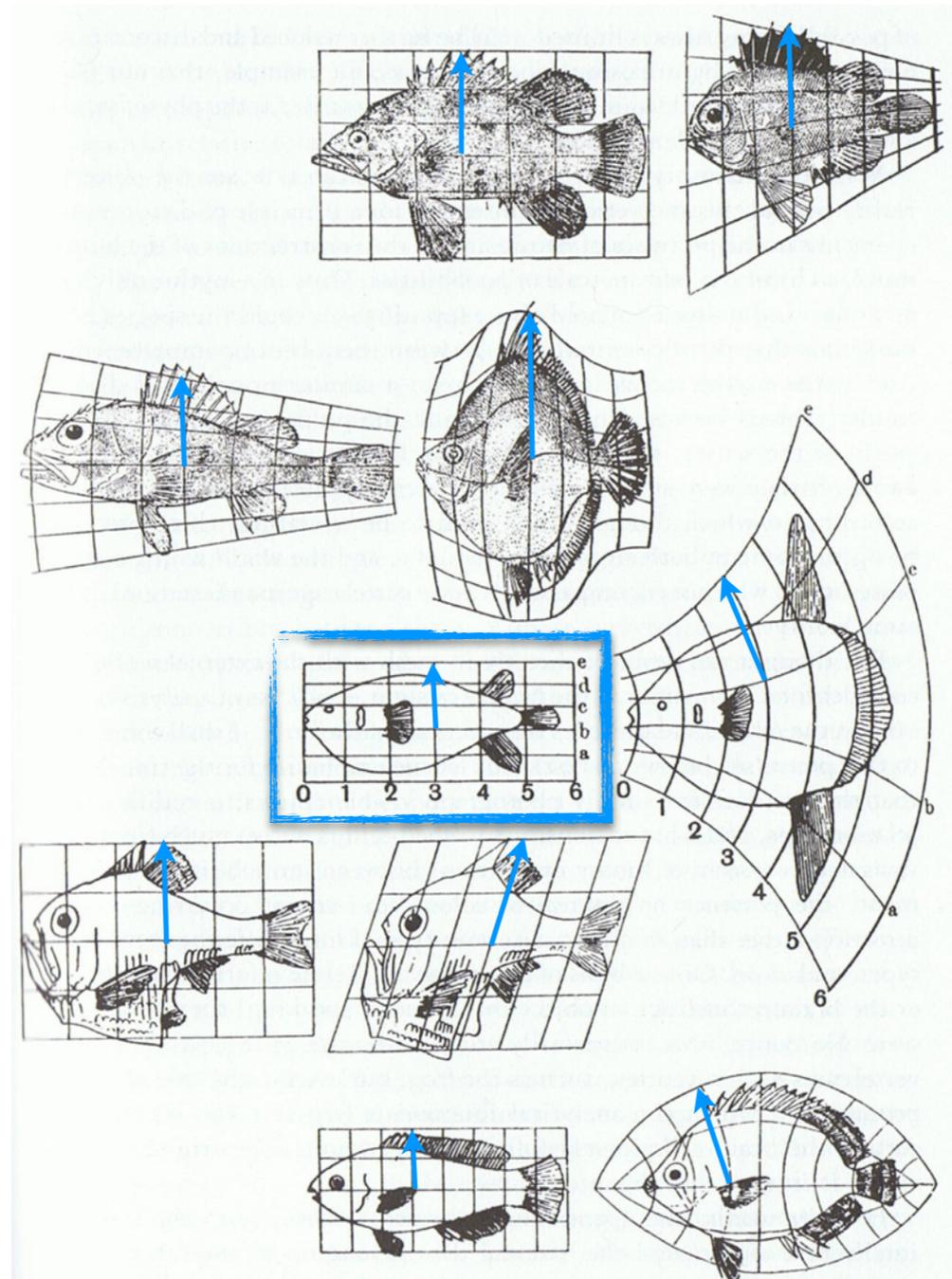
- points homologues
- type de transformation
- critère de similarité (+ régularisation)
- méthode d'optimisation

Champs denses



[Pieperhoff et al. 2008]

Opérations sur les transformations spatiales



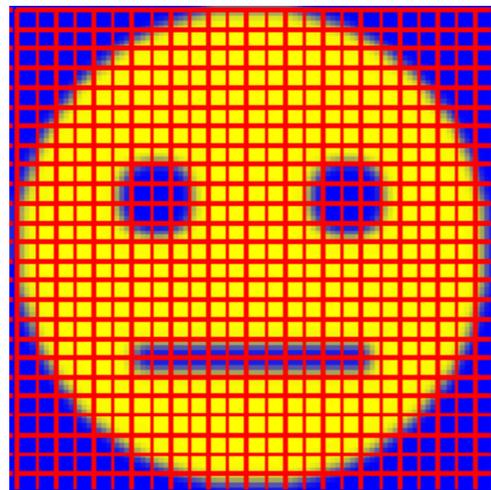
[D'Arcy Thompson 1917]

Jacobien

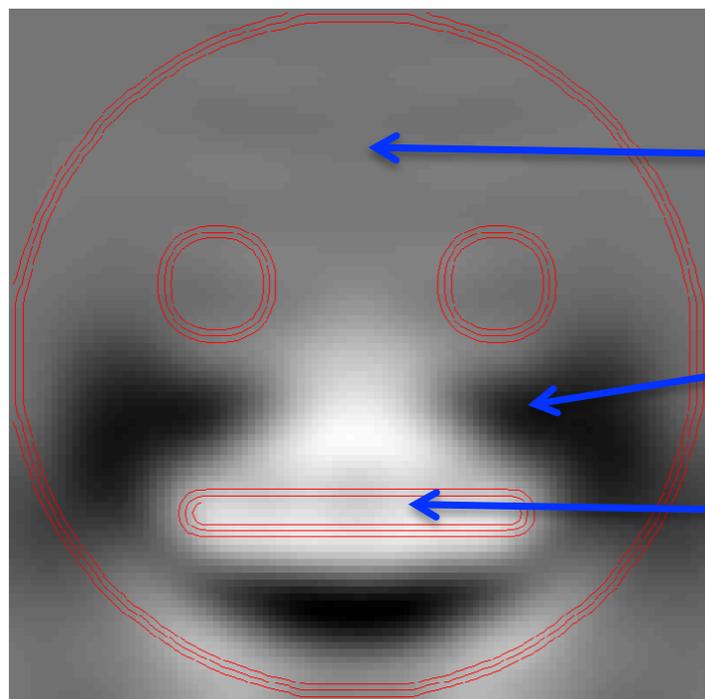
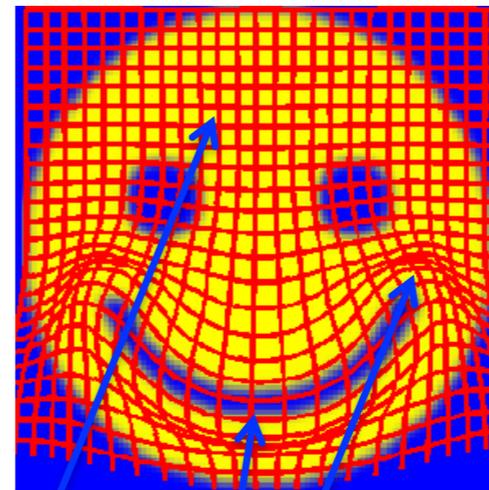
position du voxel : $\mathbf{x} = (x, y, z)$
déformation : $\mathbf{d} = (d_x, d_y, d_z)$

«jacobien» : $J(\mathbf{x}) = \det \frac{\partial \mathbf{d}(\mathbf{x})}{\partial \mathbf{x}}$

Jacobien



recalage
→

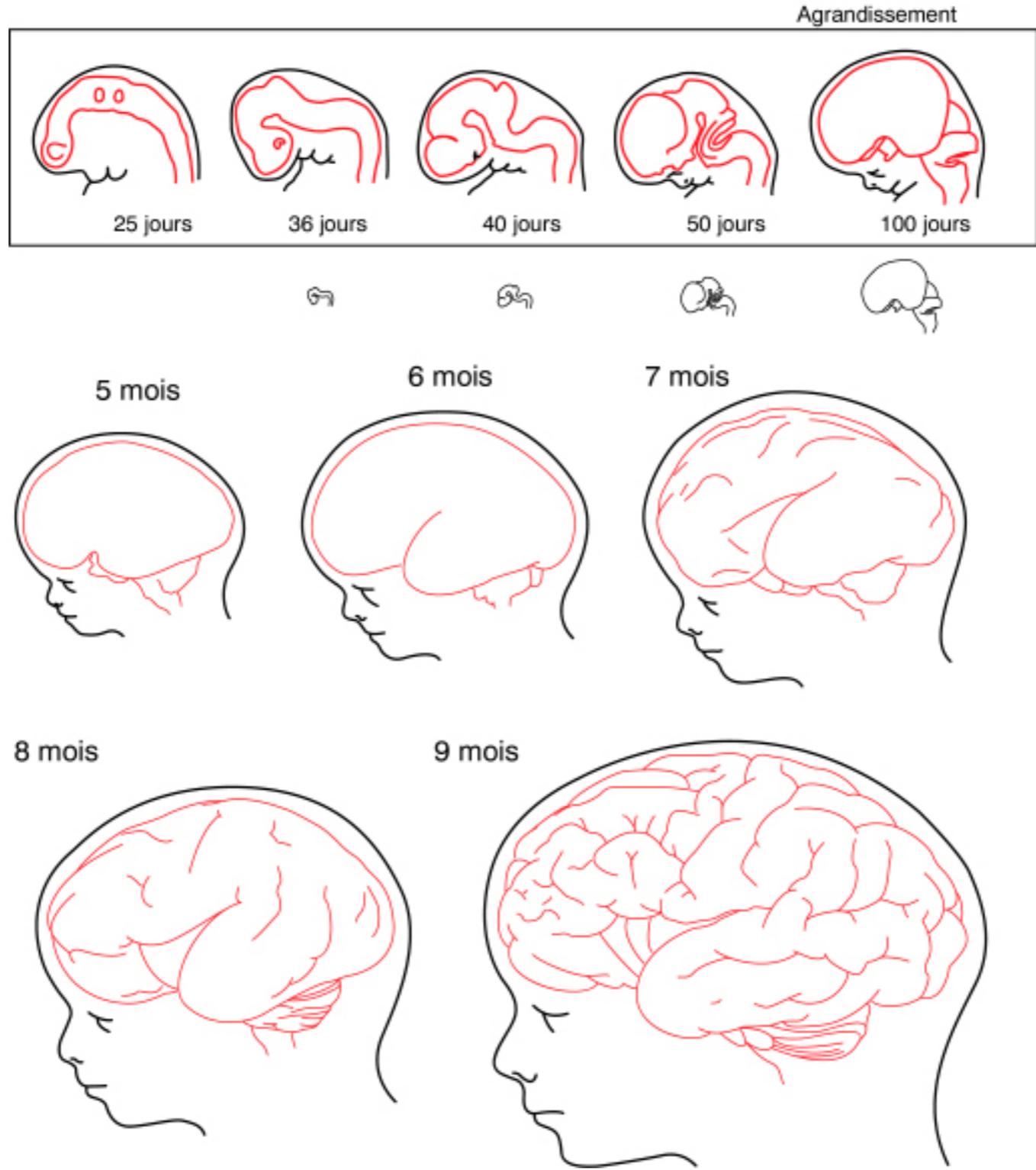


$J=1$ conservation du volume

$0 < J < 1$: contraction (diminution du volume)

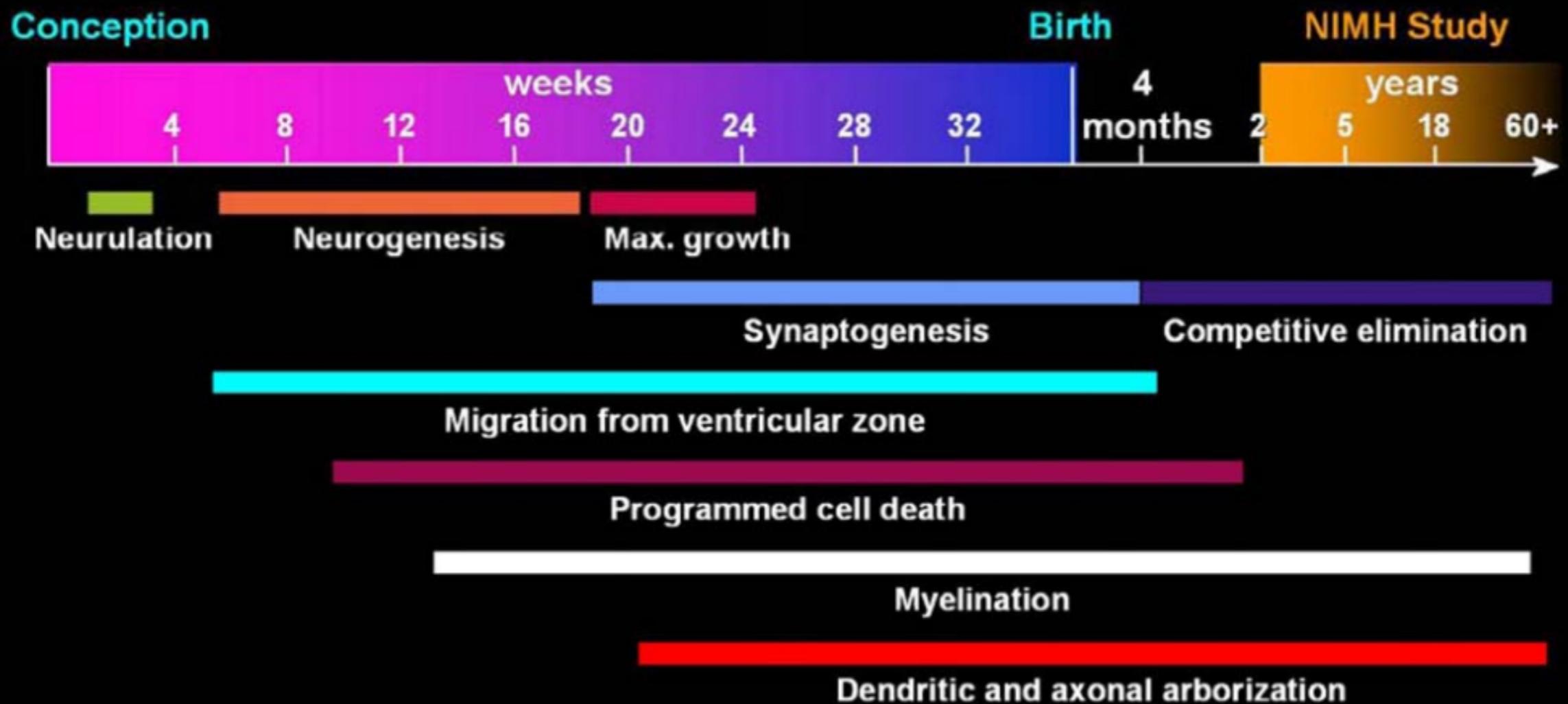
$J > 1$: dilatation (augmentation du volume)

Imagerie anténatale

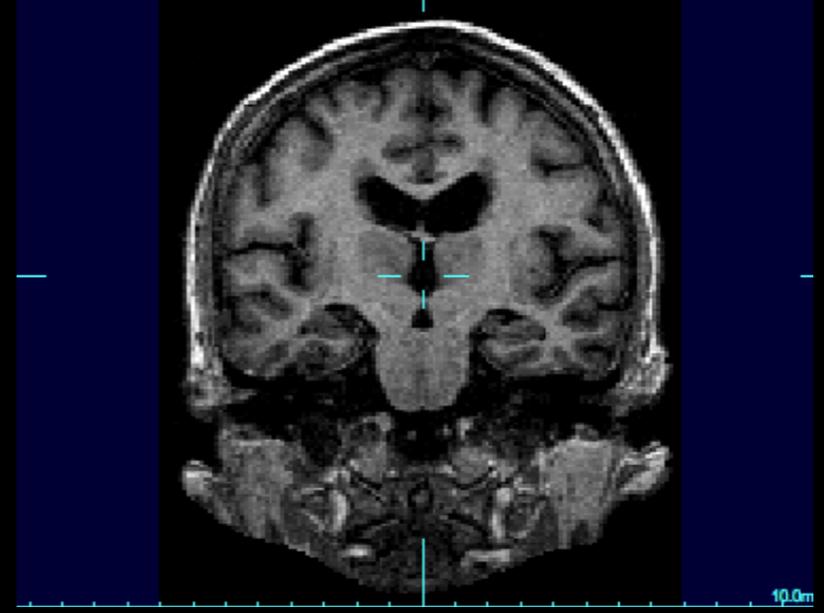
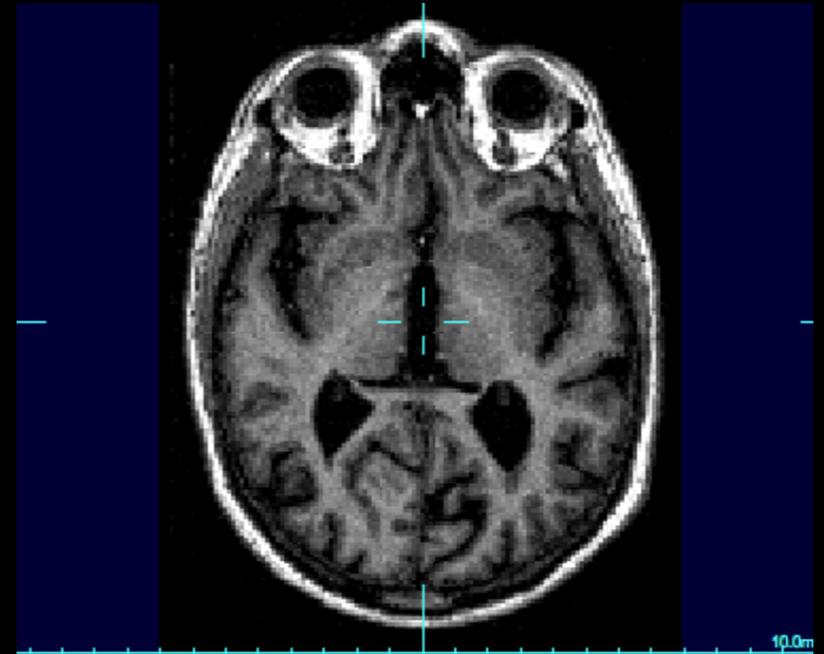
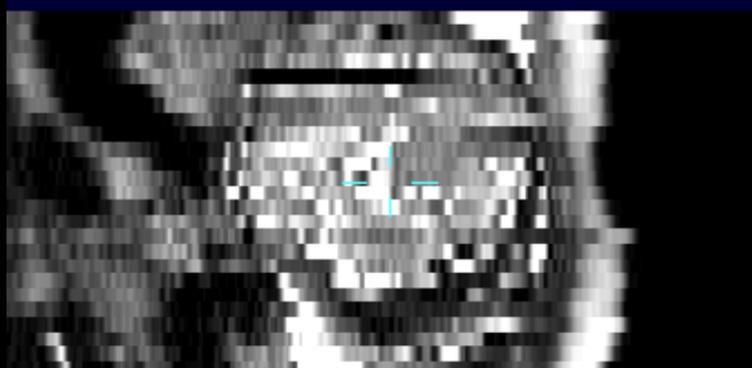
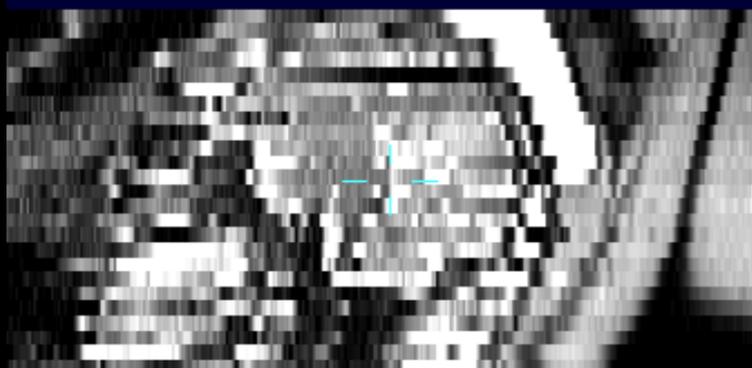
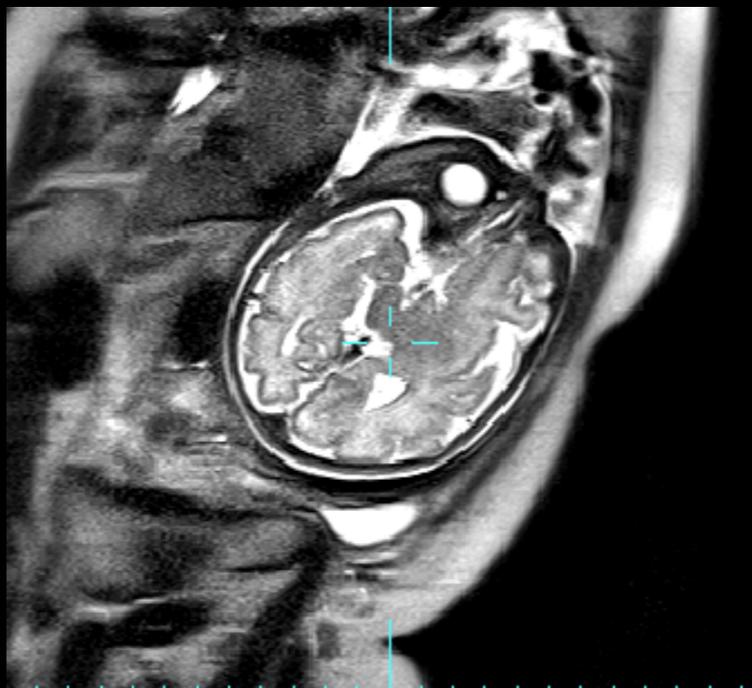


[Cowan 1979]

Time Course of Critical Events in the Determination of Human Brain Morphometry



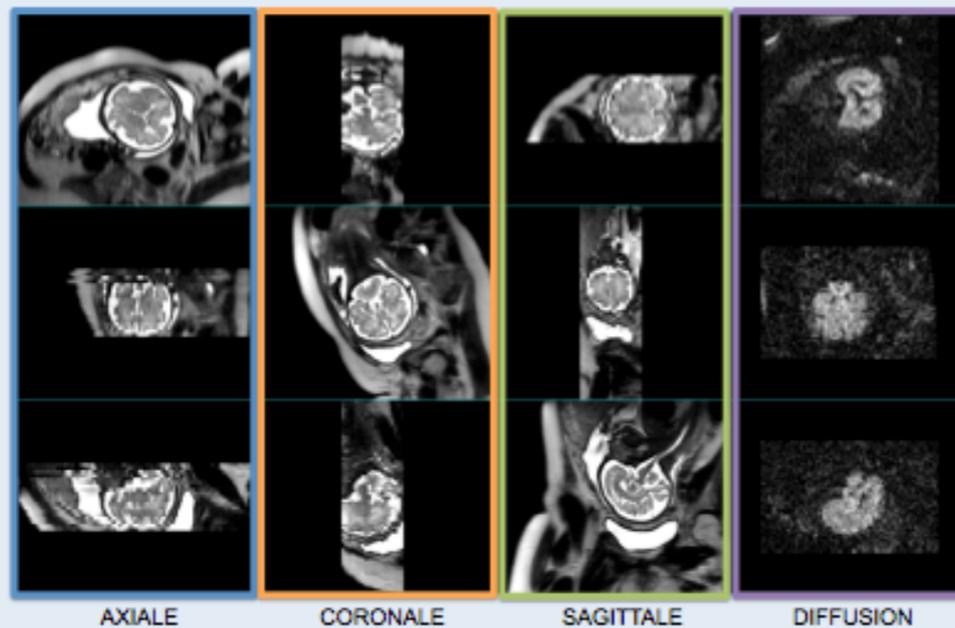




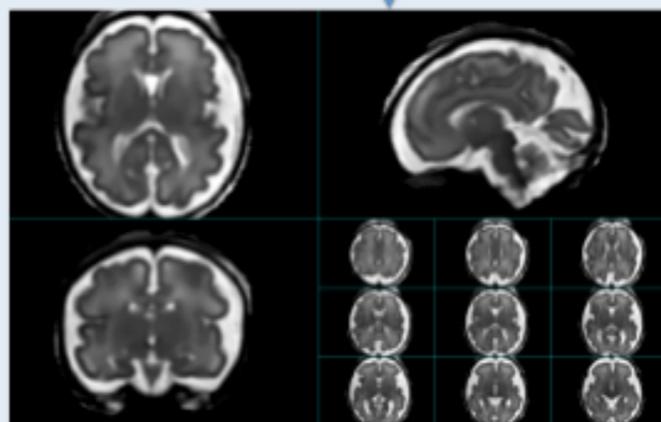
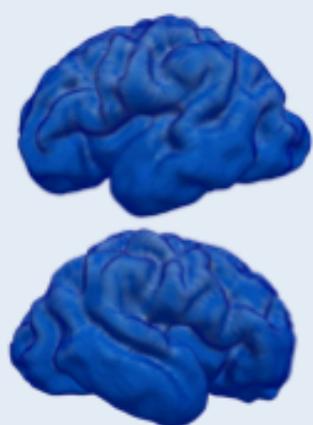
Spécificités

- Résolution anisotrope (1 x 1 x 3 mm)
- Mouvement du Foetus
 - Mouvement entre l'acquisition des coupes,
 - L'ensemble des coupes n'est pas consistant en 3D,
 - Parties de l'anatomie peuvent manquer.
- Inhomogénéité en intensité
- Contraste différent de l'IRM d'adulte
- Pas d'orientation prédéfinie

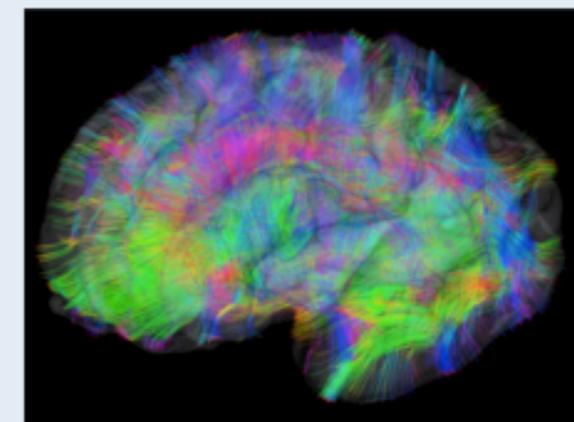
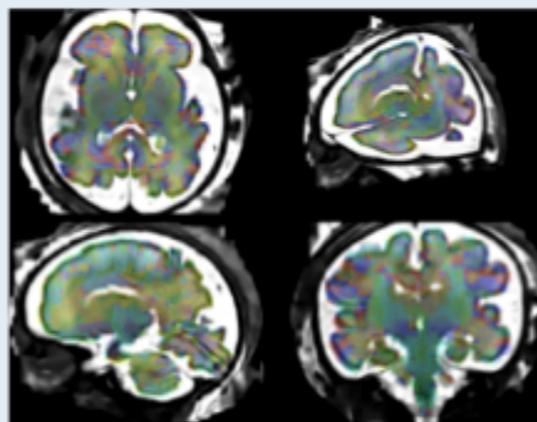
Données brutes



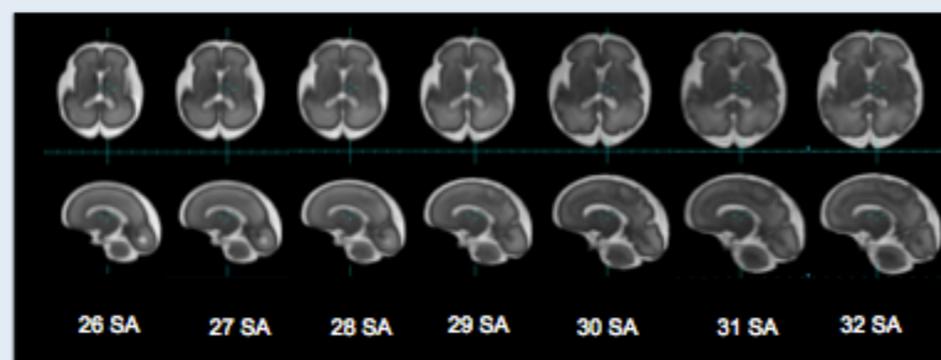
Images Anatomiques



Images de diffusion

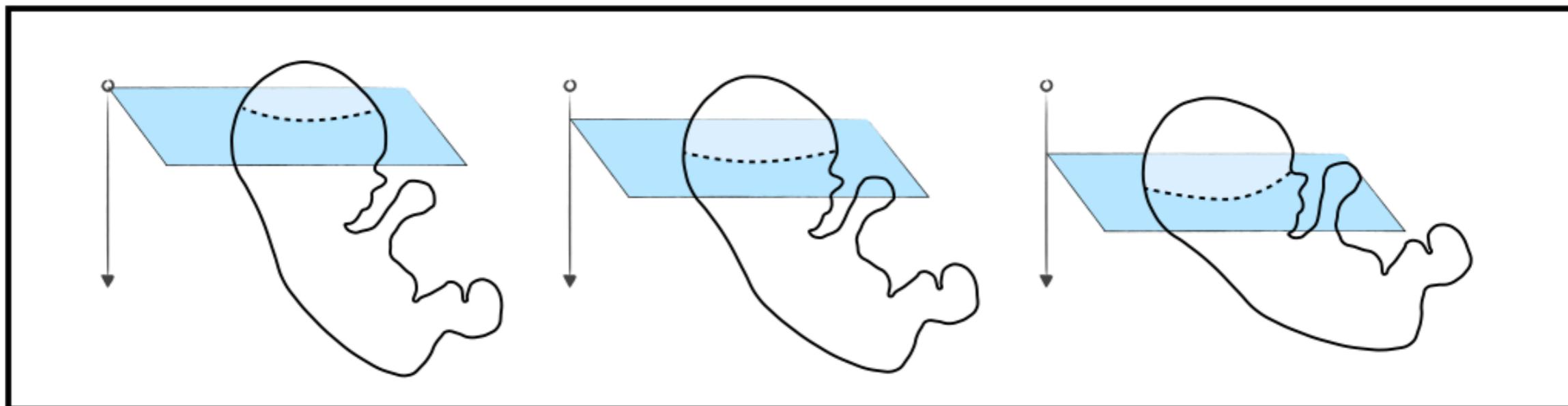


Analyse du développement cérébral *in-utero*

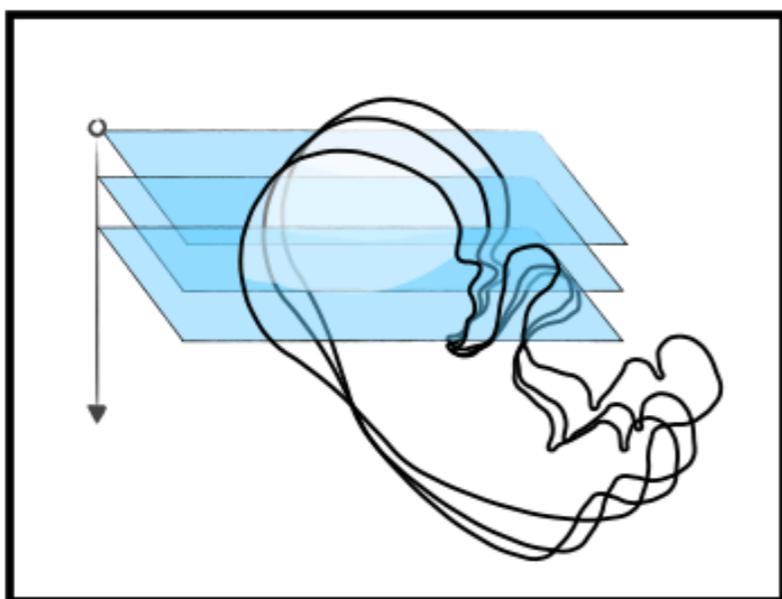


Reconstruction

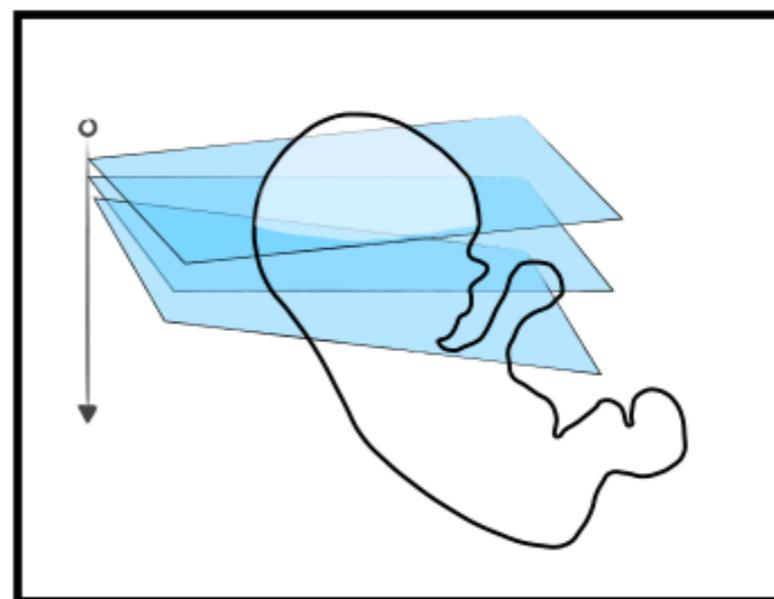
Mouvement durant l'acquisition

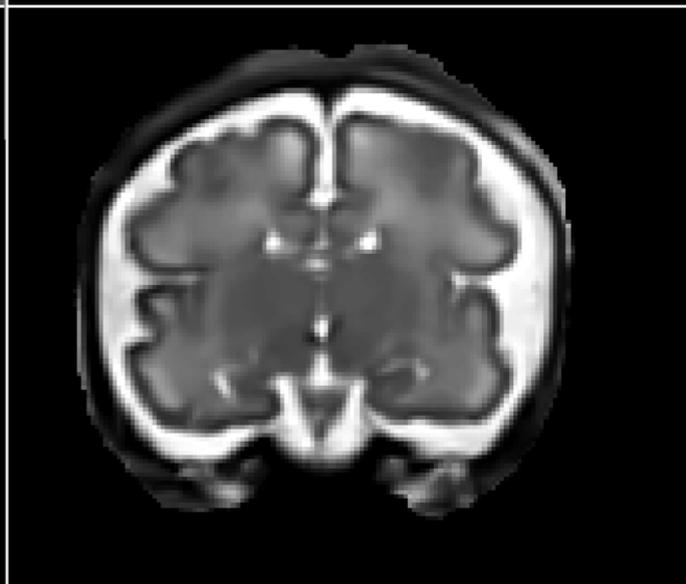
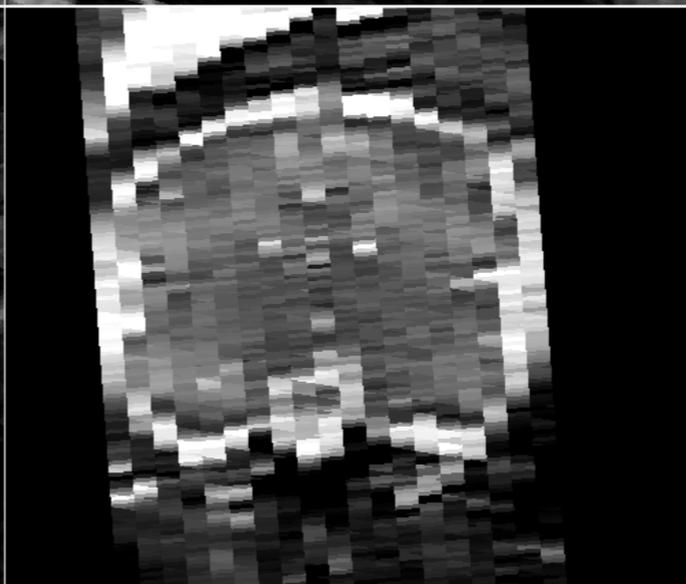
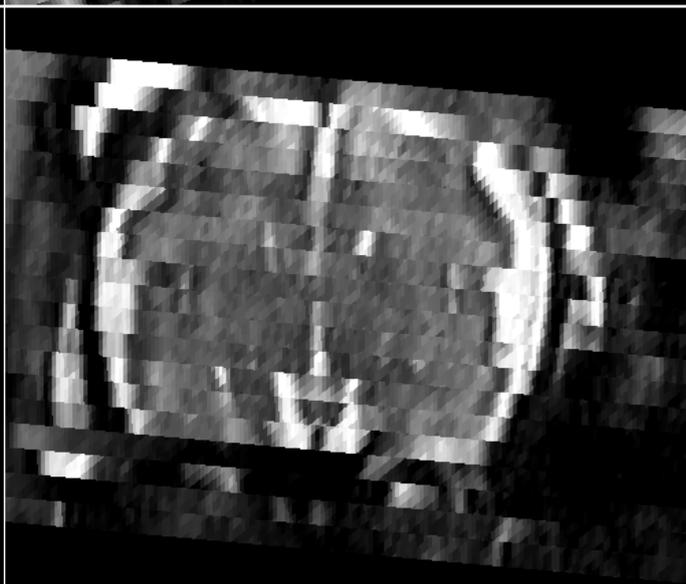
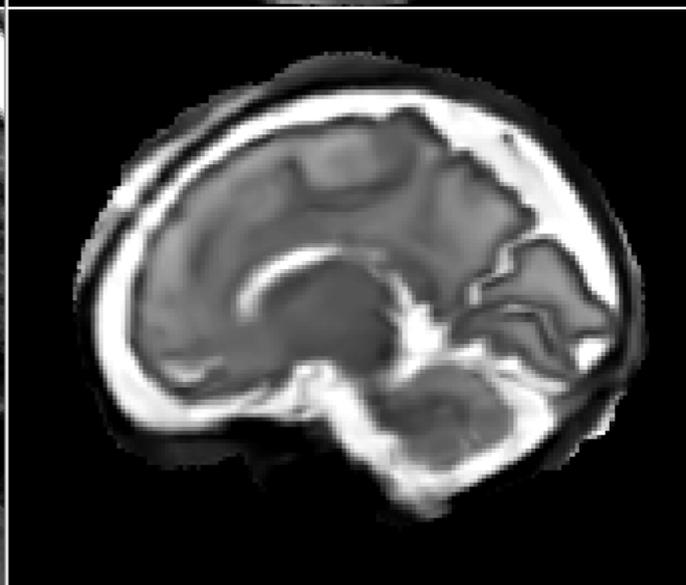
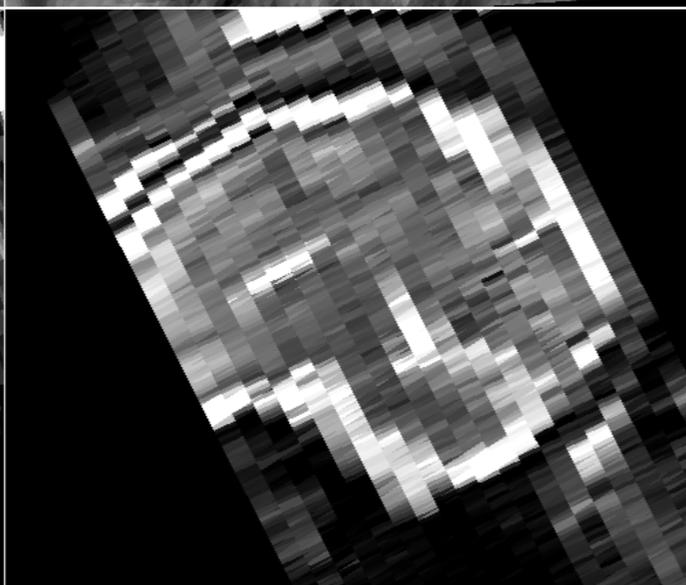
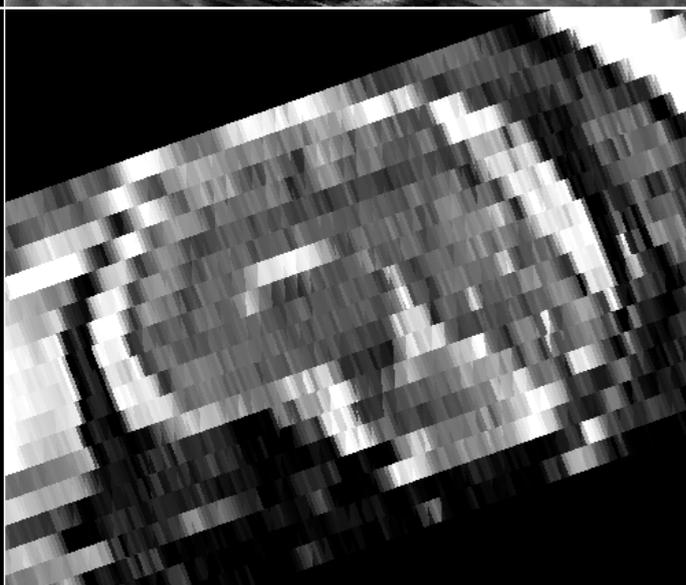
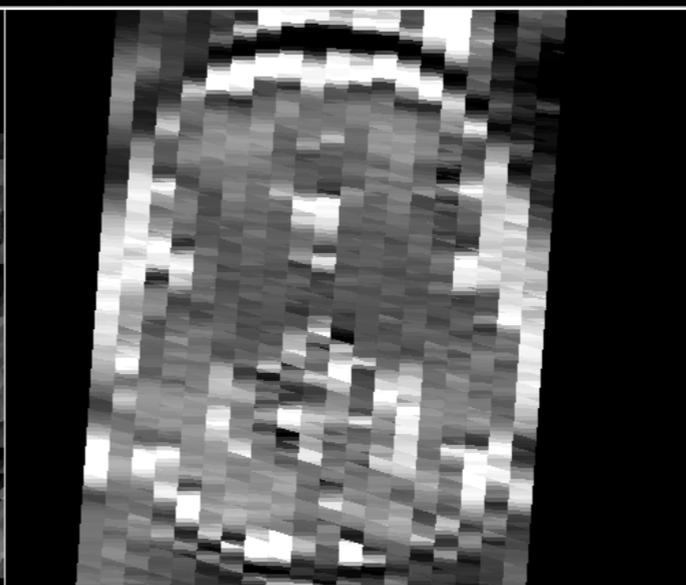


Reconstruction sans correction de mouvement



Reconstruction avec correction de mouvement





Formulation

sous échantillonnage

flou

biais

mouvement

nombre
d'images

nombre
de coupes

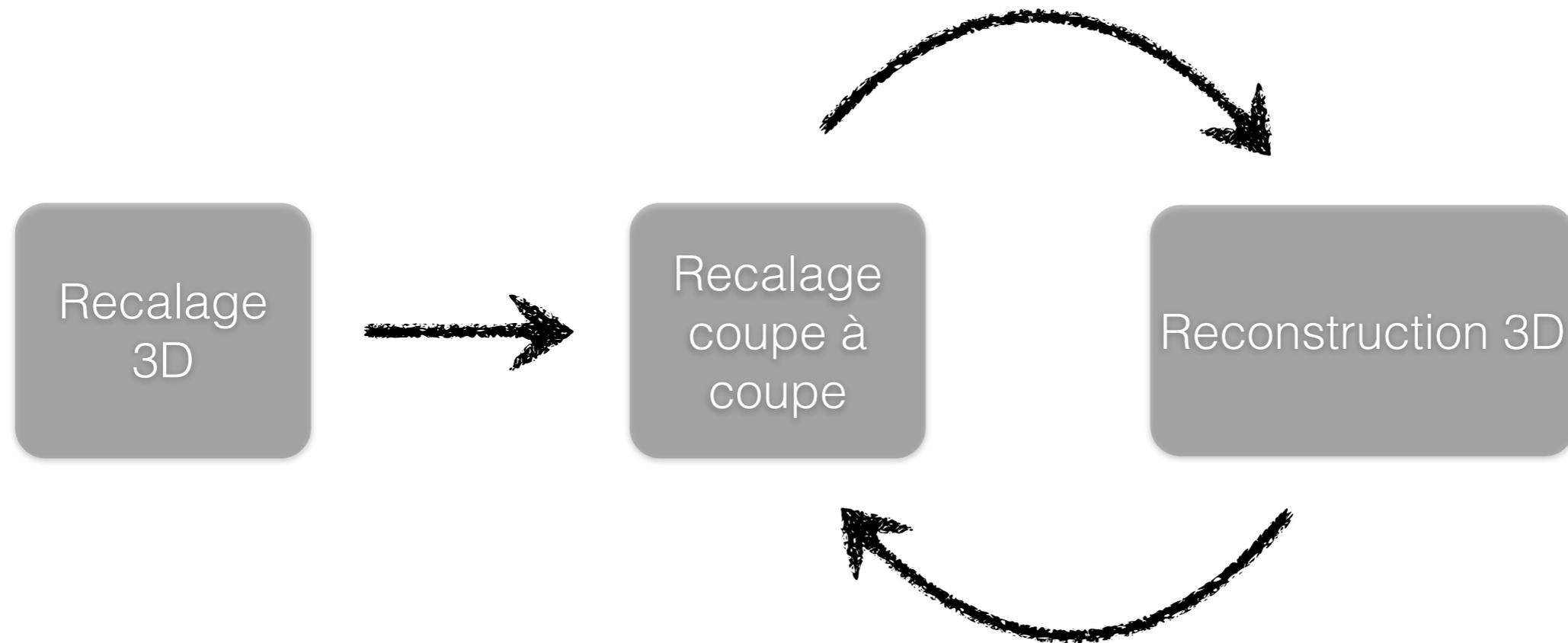
$$\mathbf{y}_{\mathbf{r},\mathbf{s}} = S_r F_r B_{r,s} W_s W_r \mathbf{x} + \mathbf{n}_r \quad \text{for } 1 \leq r \leq n, \quad 1 \leq s \leq m_r$$

observations

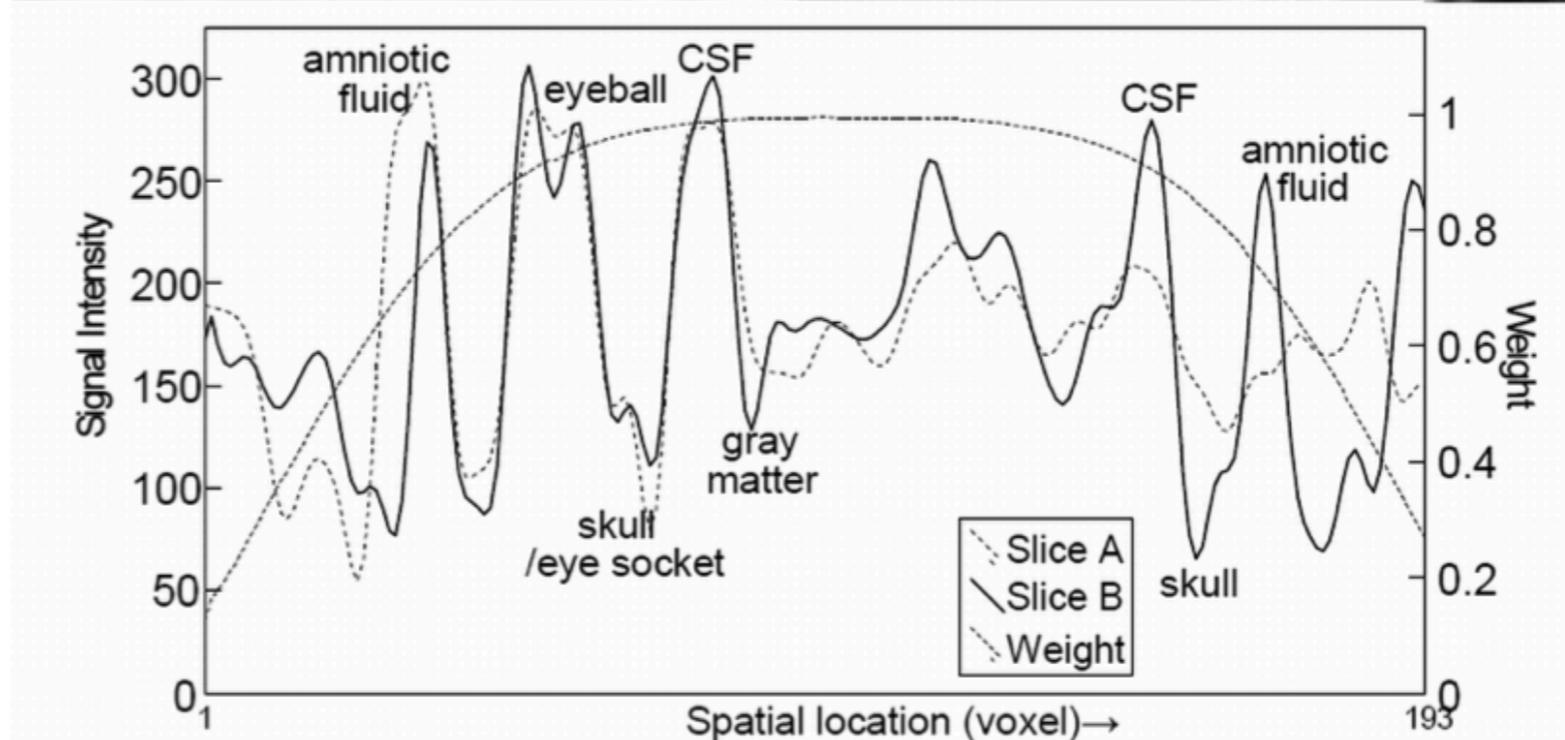
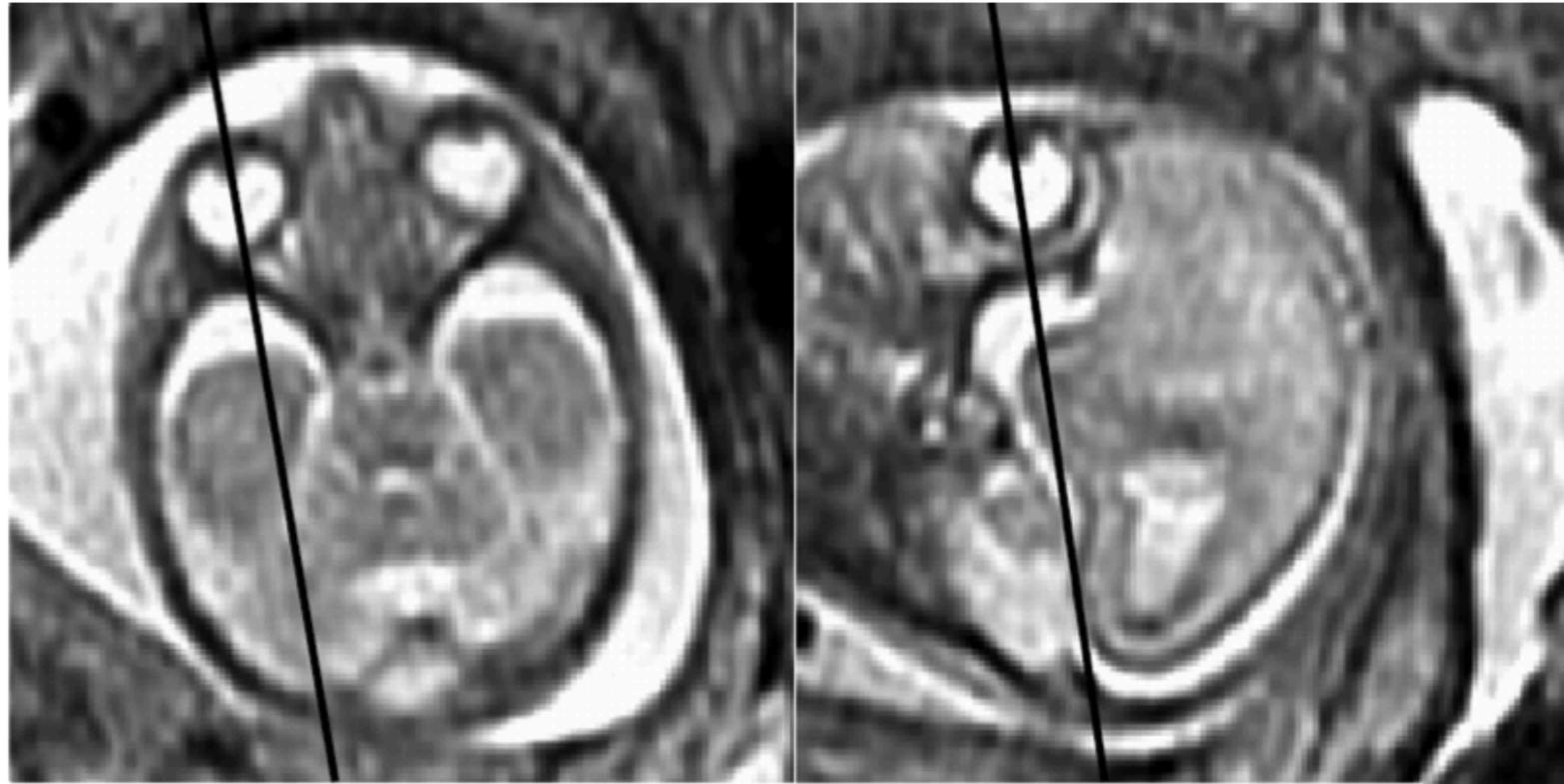
image 3D

bruit

Correction de mouvement



Correction du mouvement



Super résolution

formulation générale

$$\mathbf{y} = f(\mathbf{x}) + \mathbf{n}$$

approche variationnelle

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x}} \|\mathbf{y} - f(\mathbf{x})\|^2 + \lambda J(\mathbf{x})$$

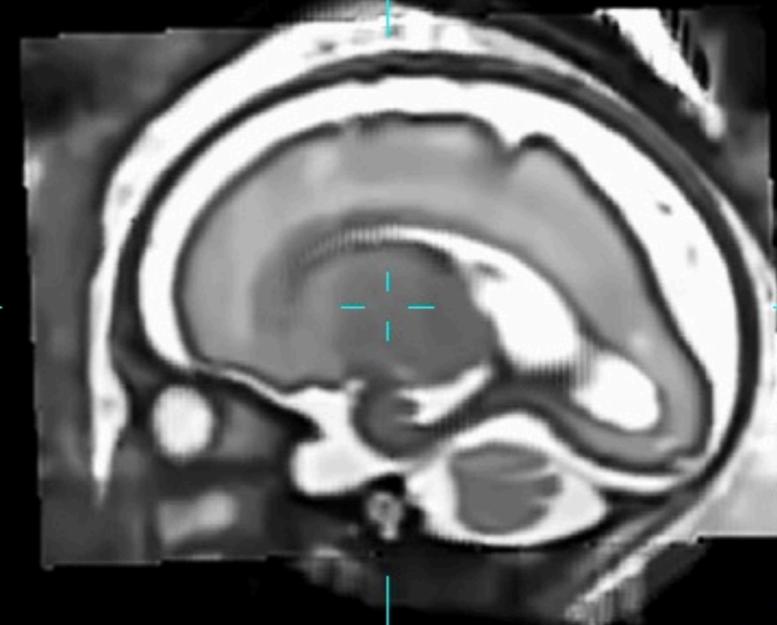
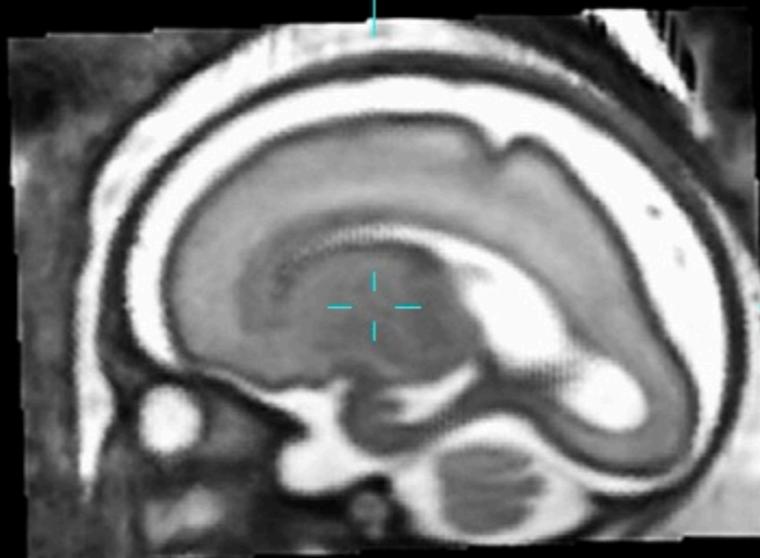
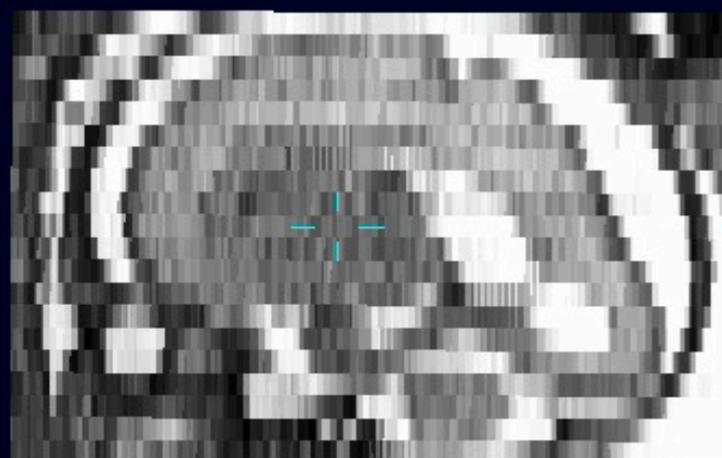
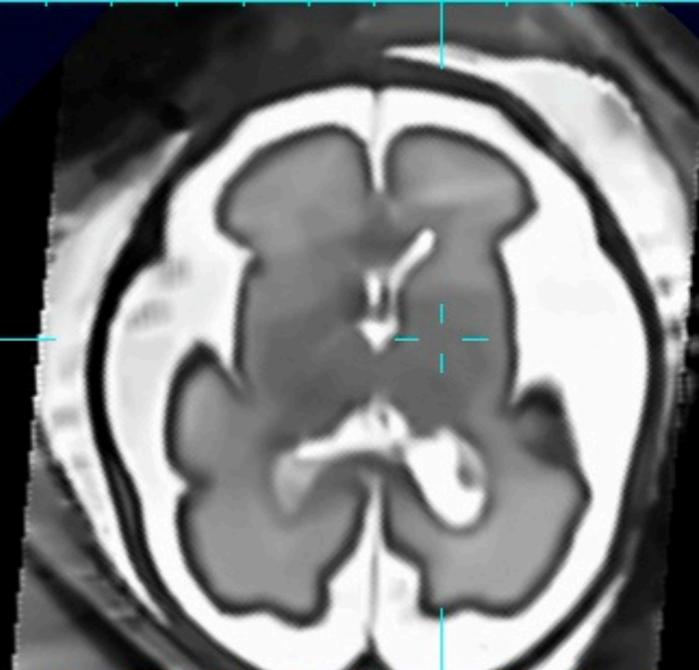
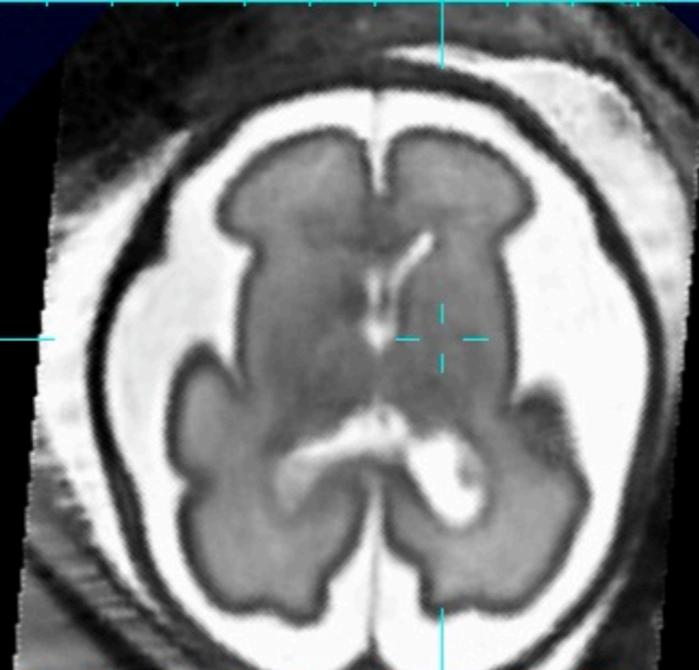
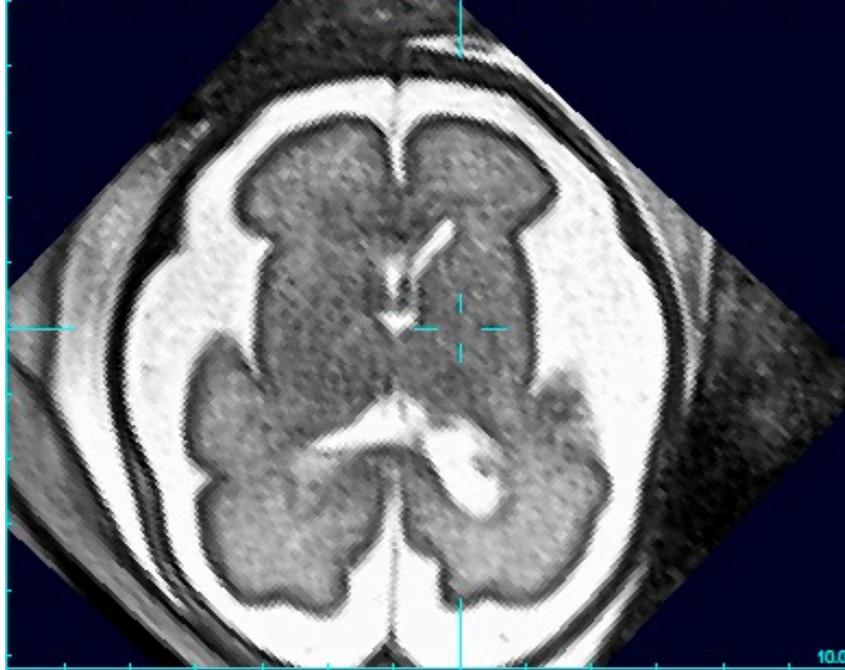
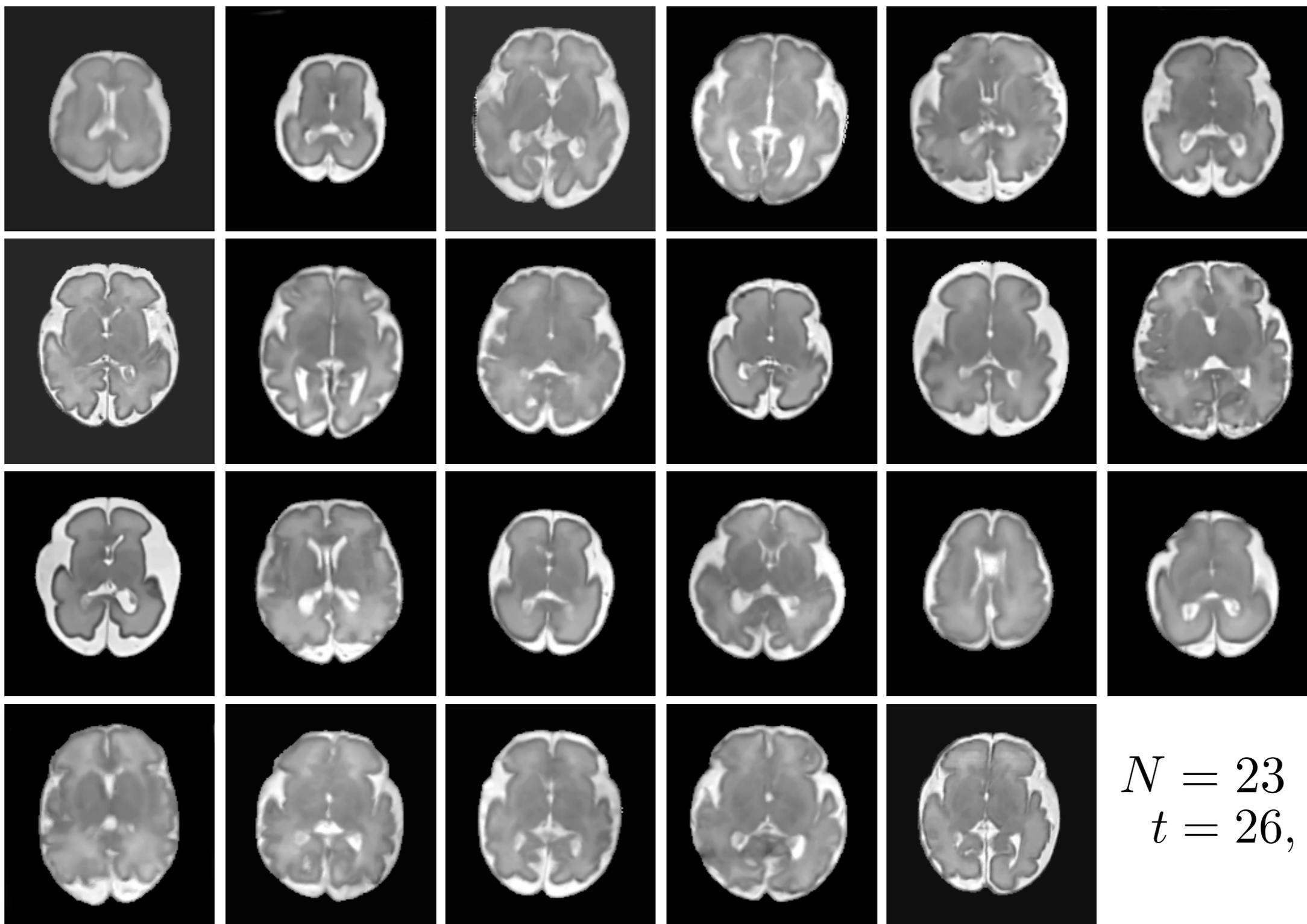


Image originale

Image HR (interpolation)

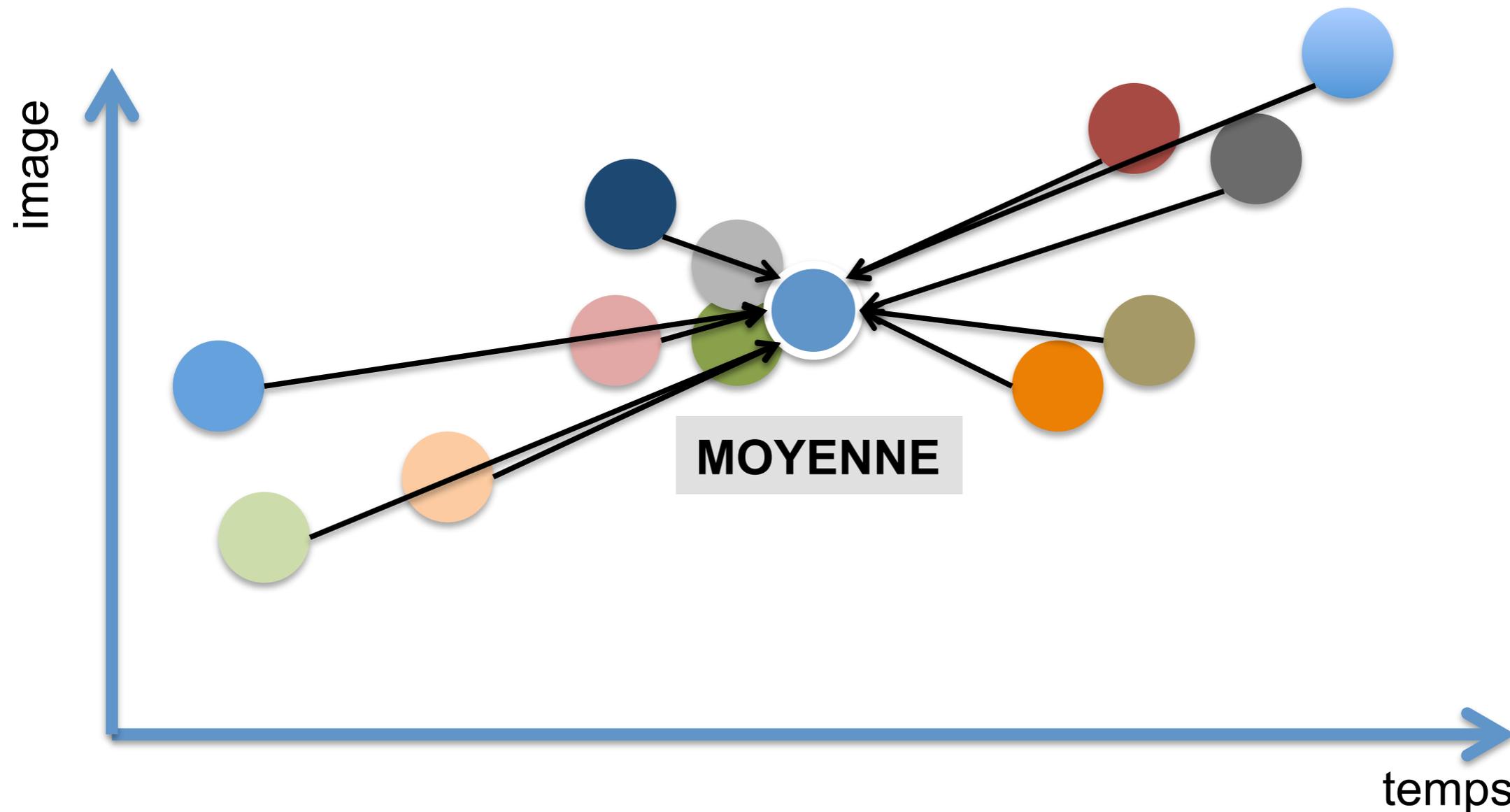
Image HR (SR)

Atlas



$N = 23$
 $t = 26, \dots, 34$

Atlas «statistique»



Moyenne: barycentre de la population

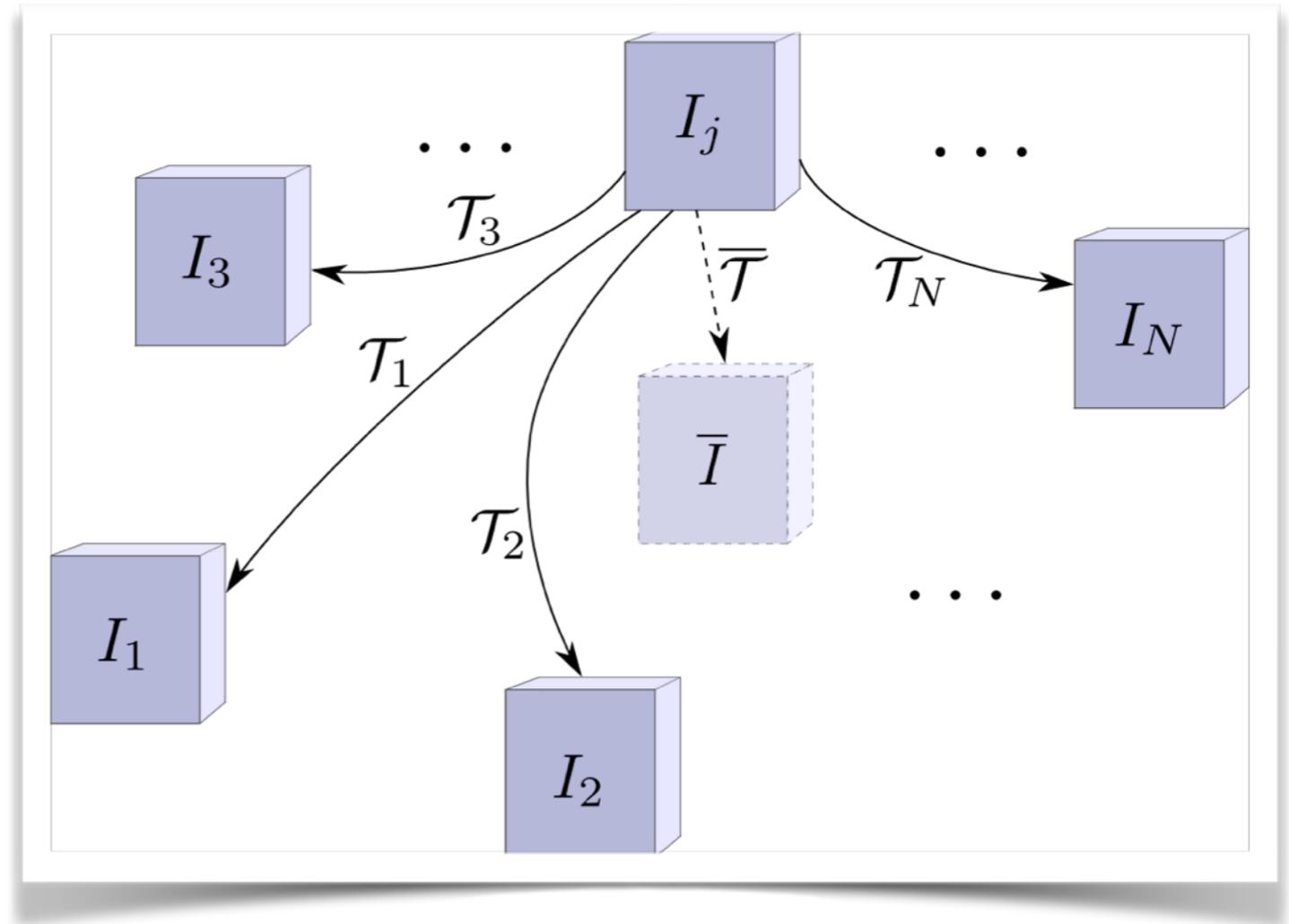
(i.e. la somme des déformations de chaque image vers cette moyenne est nulle)

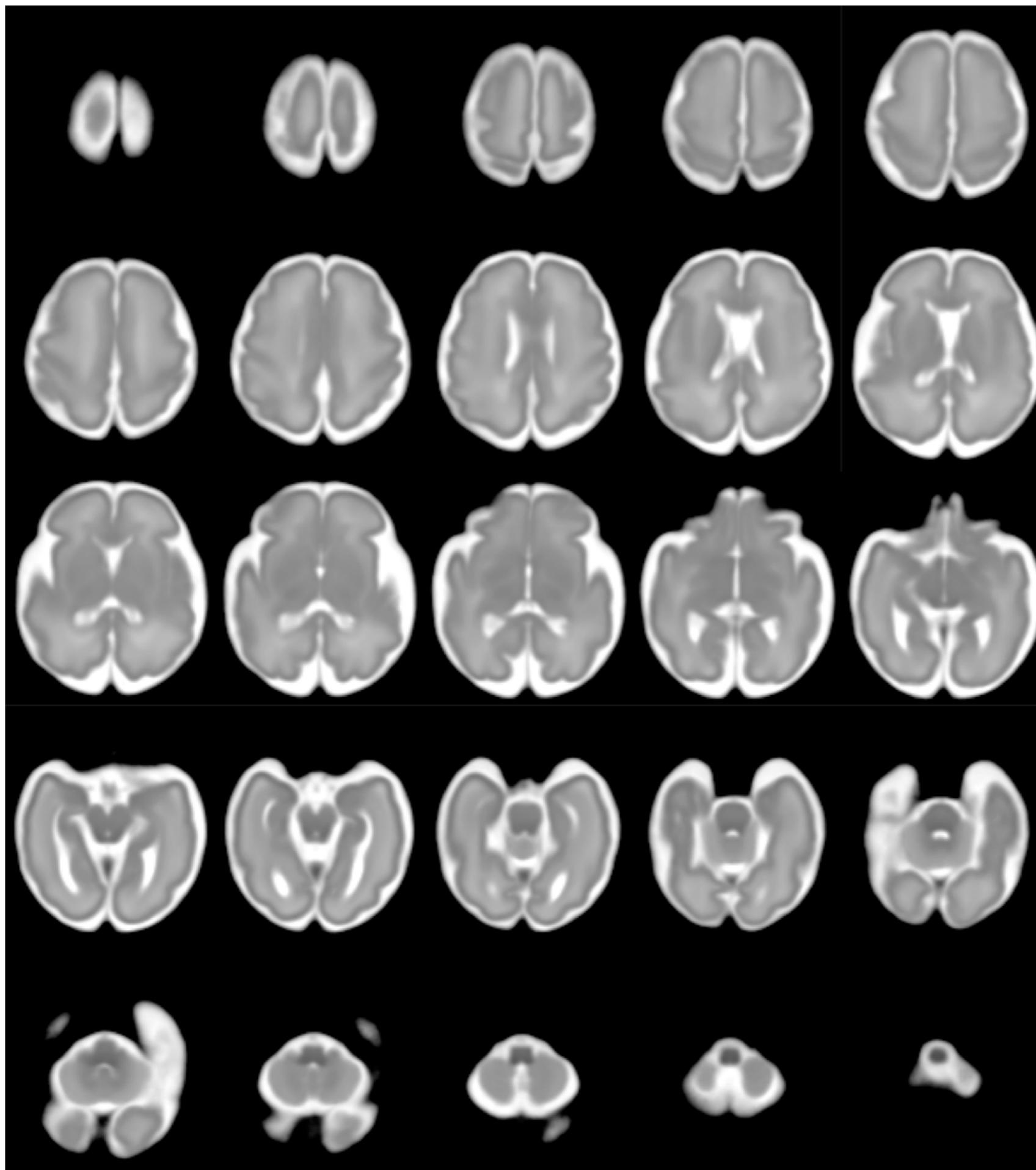
Rmq: un atlas peut contenir plus d'informations qu'une image moyenne.

Atlas «statistique»

$$\bar{\mathcal{T}} = \frac{1}{N} \sum_{i=1}^N \mathcal{T}_i$$

$$\bar{I} = \frac{1}{N} \sum_{i=1}^N \bar{\mathcal{T}} \circ \mathcal{T}_i^{-1}(I_i)$$

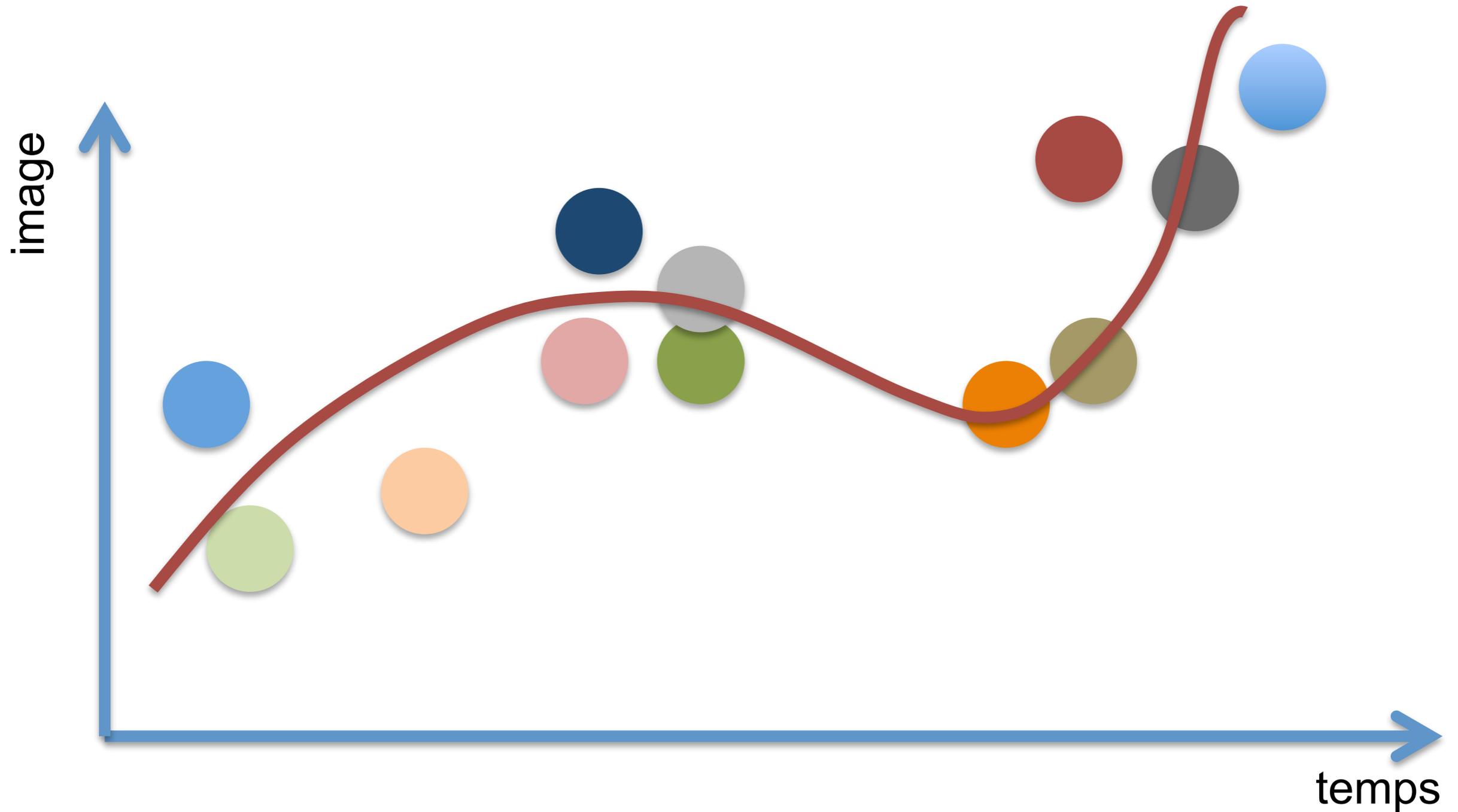




$N = 23$
 $t = 26, \dots, 34$

Atlas spatial foetal vu en coupes axiales

Image moyenne temporelle



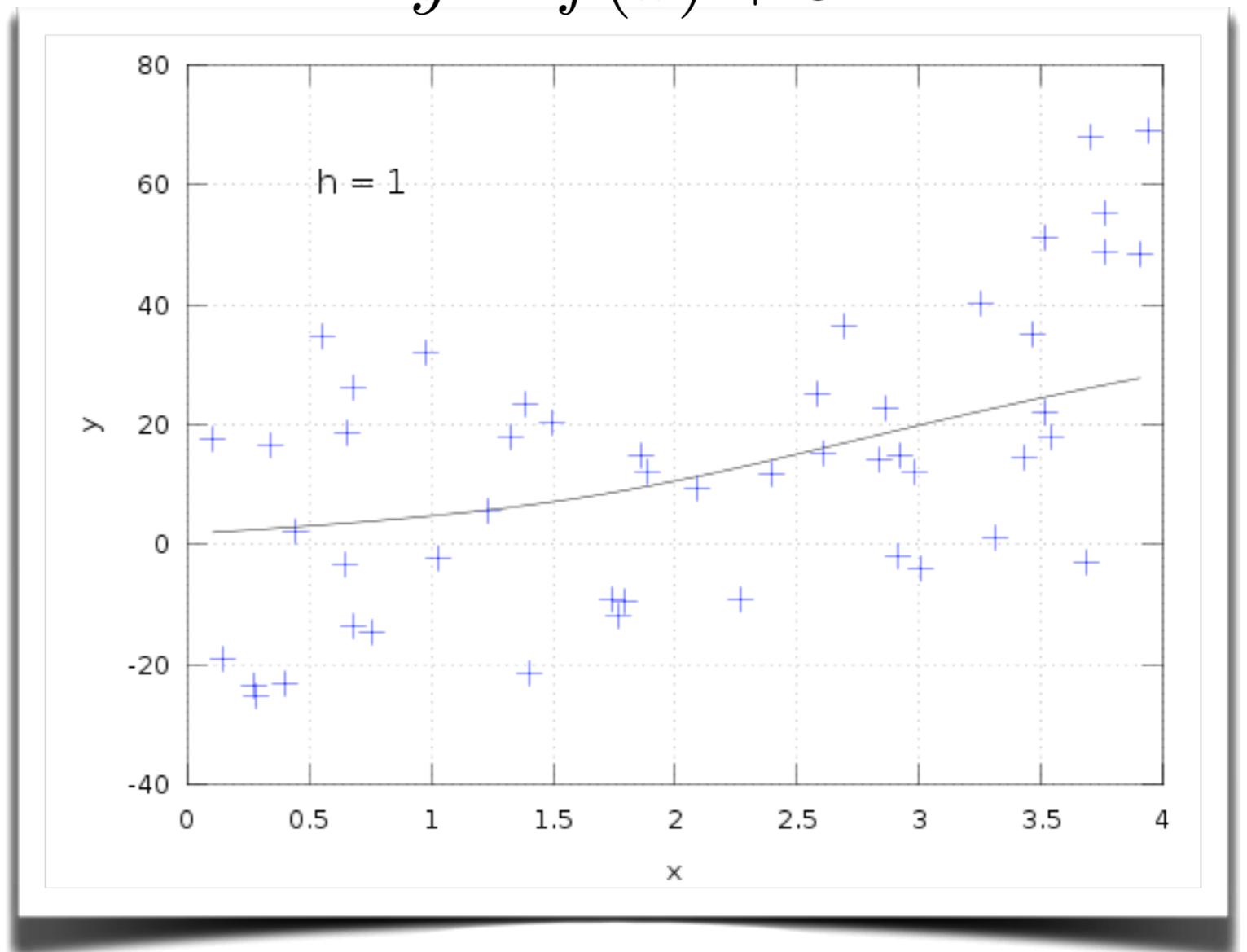
Régression

- Méthode non-paramétrique (Nadaraya-Watson 1964)
- Paramètre de lissage h

$$y = f(x) + \varepsilon$$

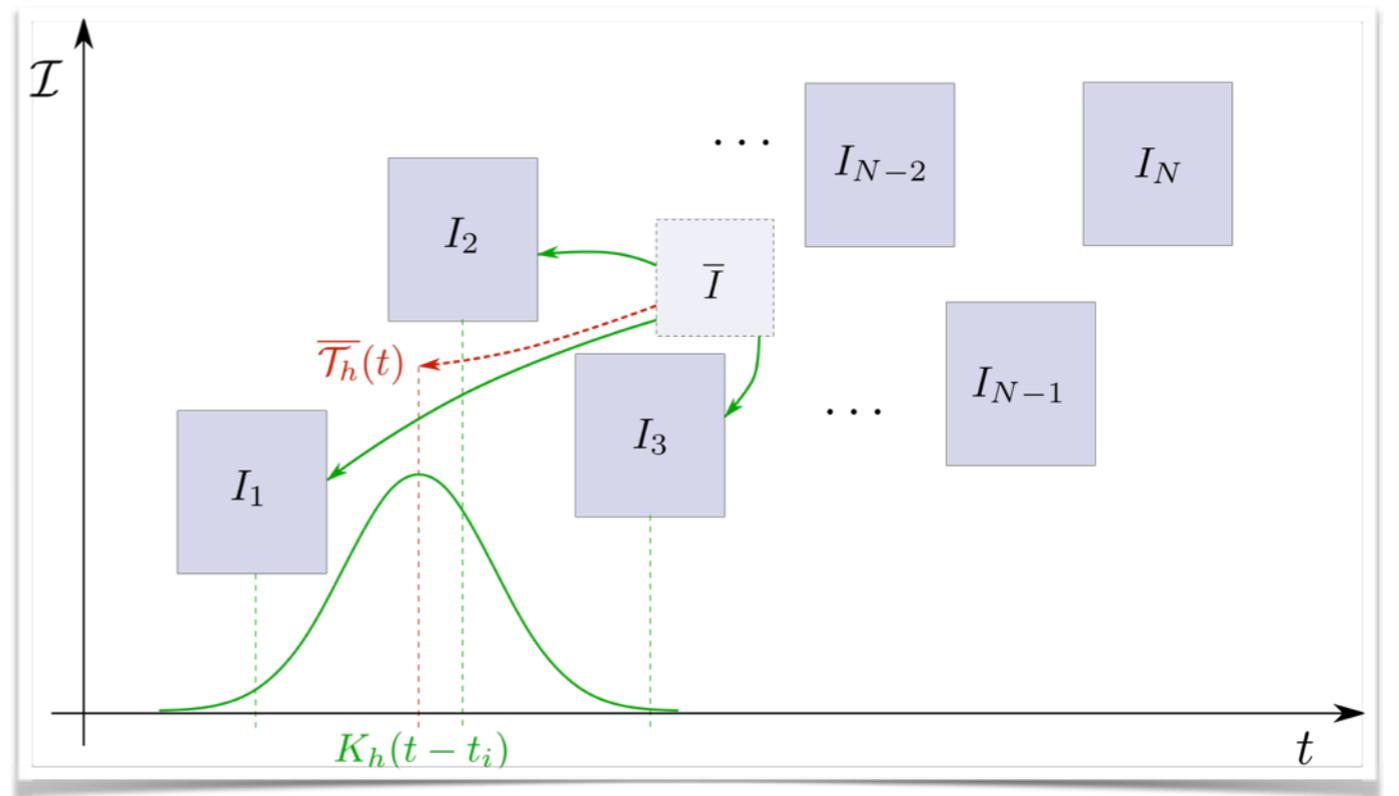
$$\hat{f}(x) = \sum_{i=1}^N w_i(x) y_i$$

$$w_i(x) = \frac{K_h(x - x_i)}{\sum_{i=1}^N K_h(x - x_i)}$$



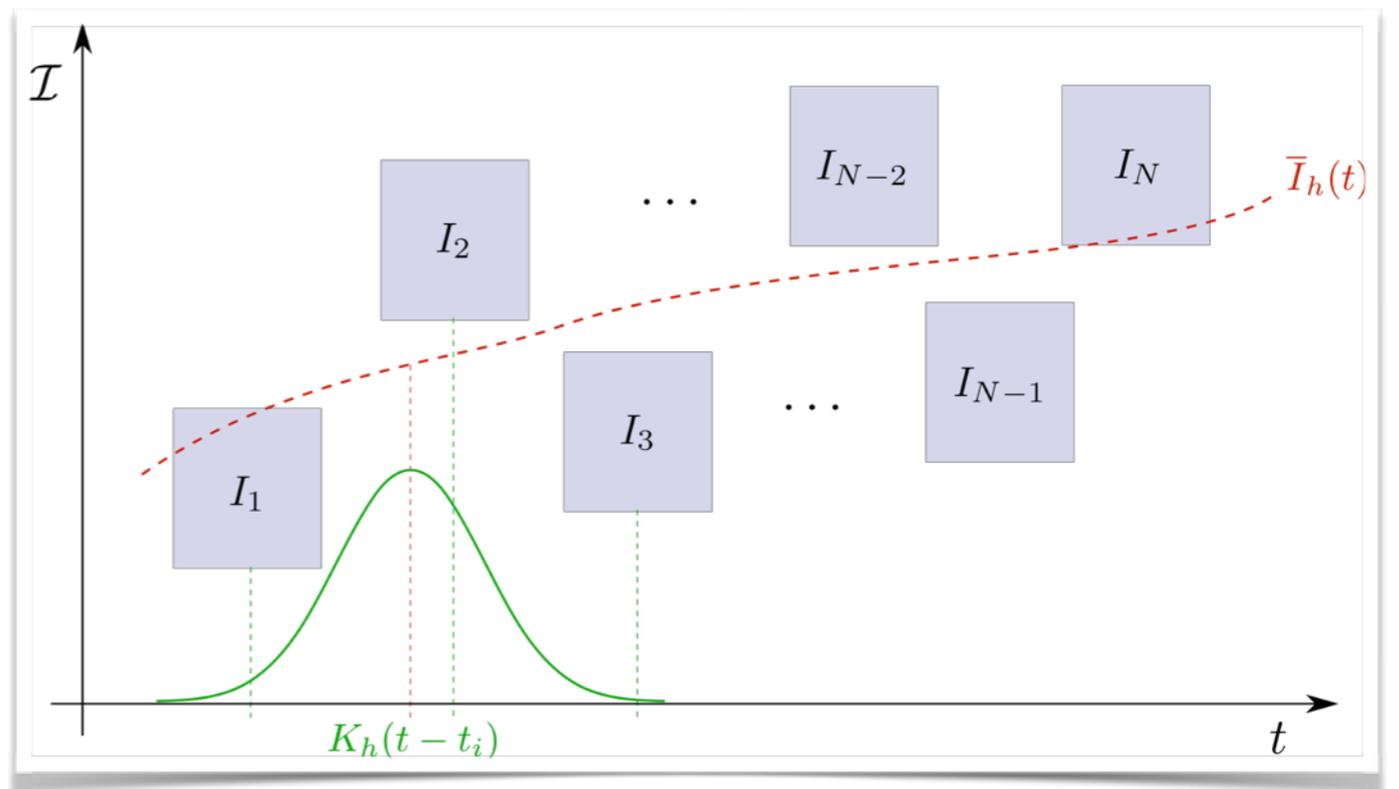
Régression sur les transformations

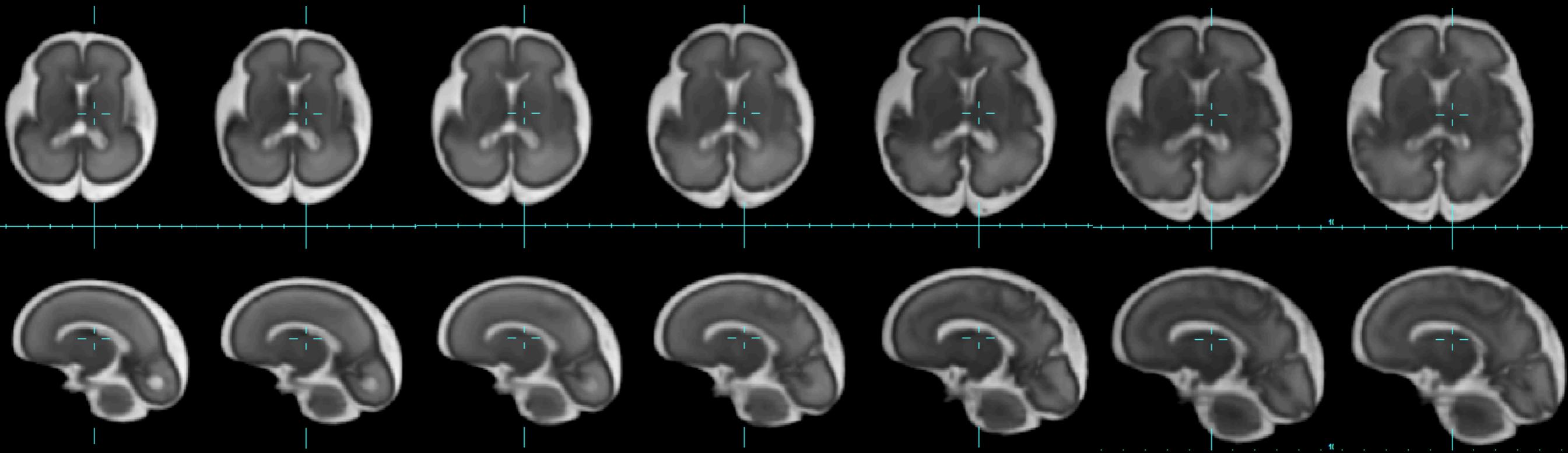
$$\bar{\mathcal{T}}(t) = \sum_{i=1}^N w_i(t) \bar{\mathcal{T}} \circ \mathcal{T}_i^{-1}$$



Régression sur les intensités

$$\bar{I}(t) = \sum_{i=1}^N w_i(t) \bar{\mathcal{T}}(t) \circ \bar{\mathcal{T}} \circ \mathcal{T}_i^{-1}(I_i)$$





26 SA

27 SA

28 SA

29 SA

30 SA

31 SA

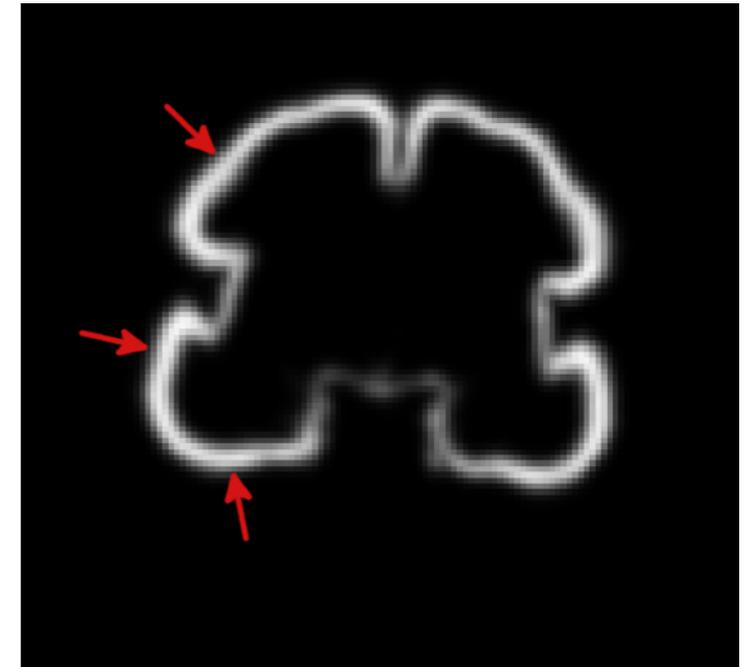
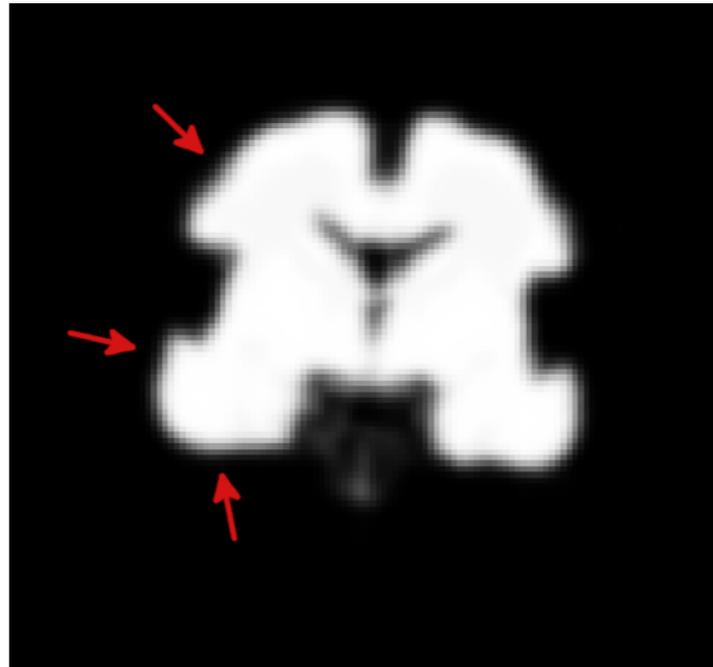
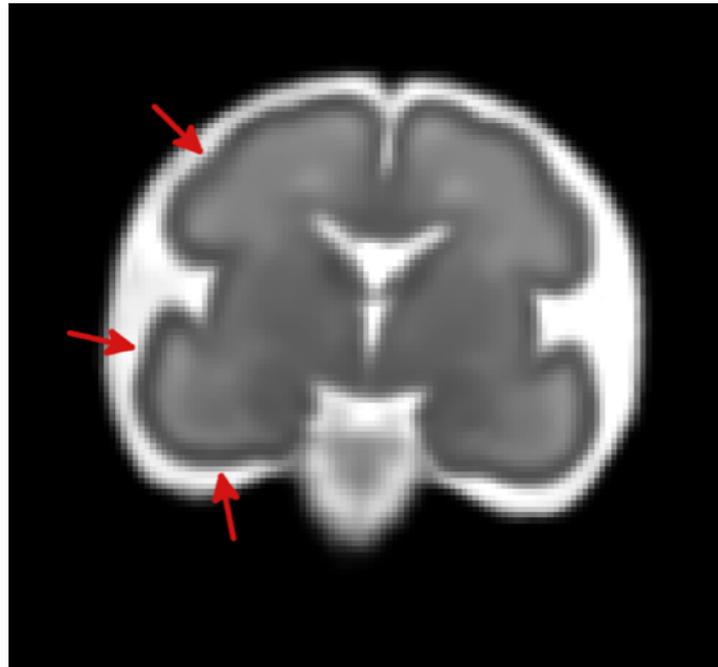
32 SA

IRM T2

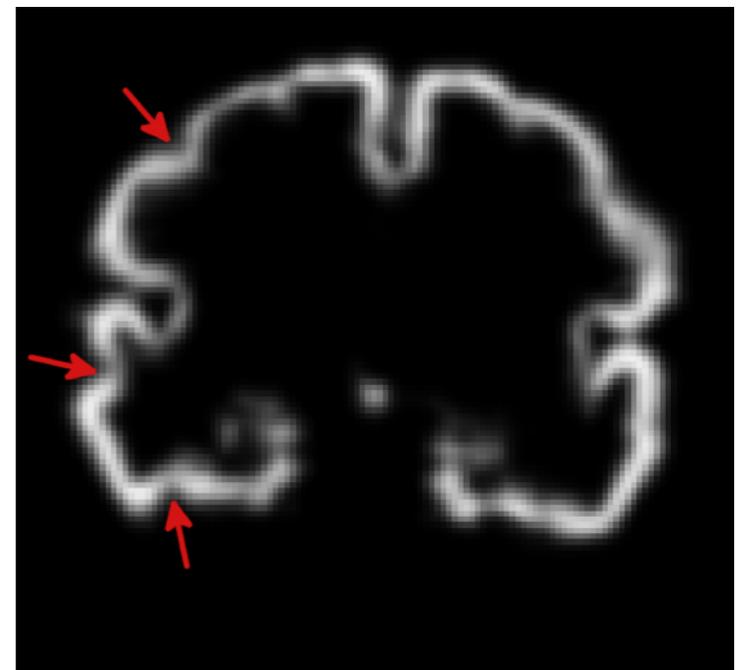
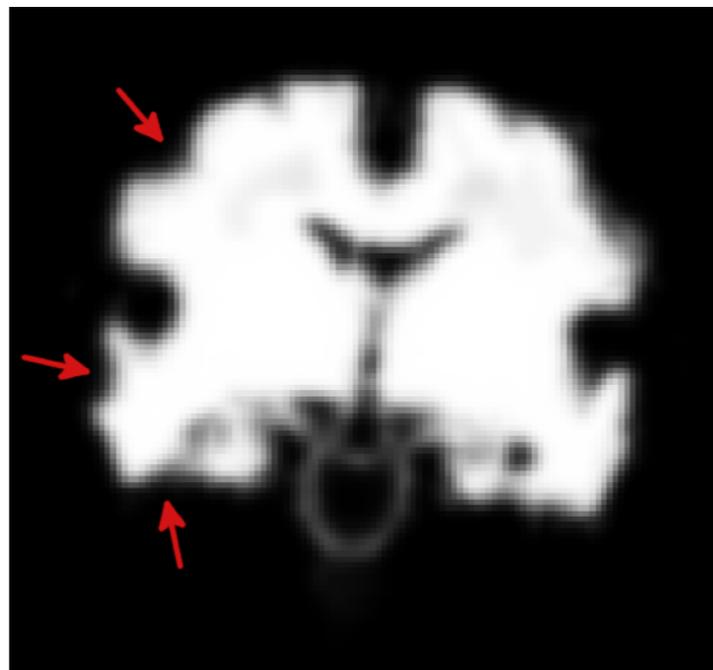
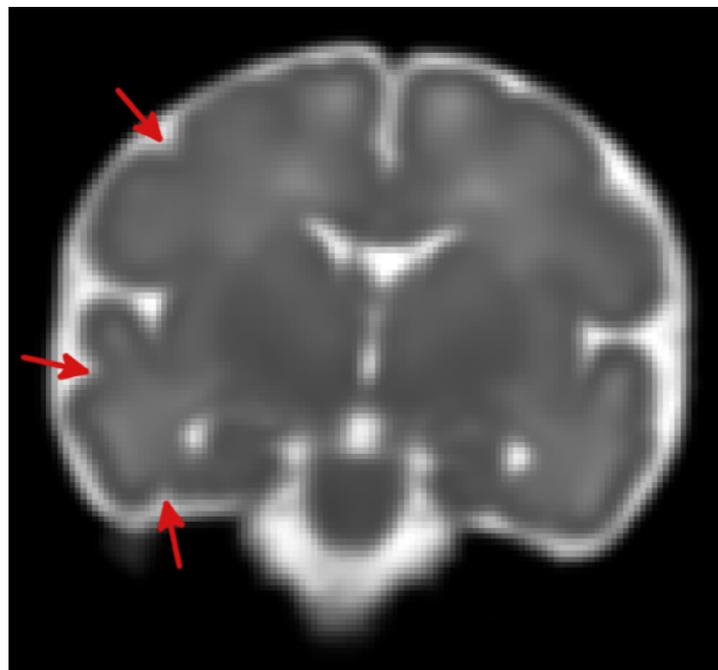
Substance blanche

Substance grise

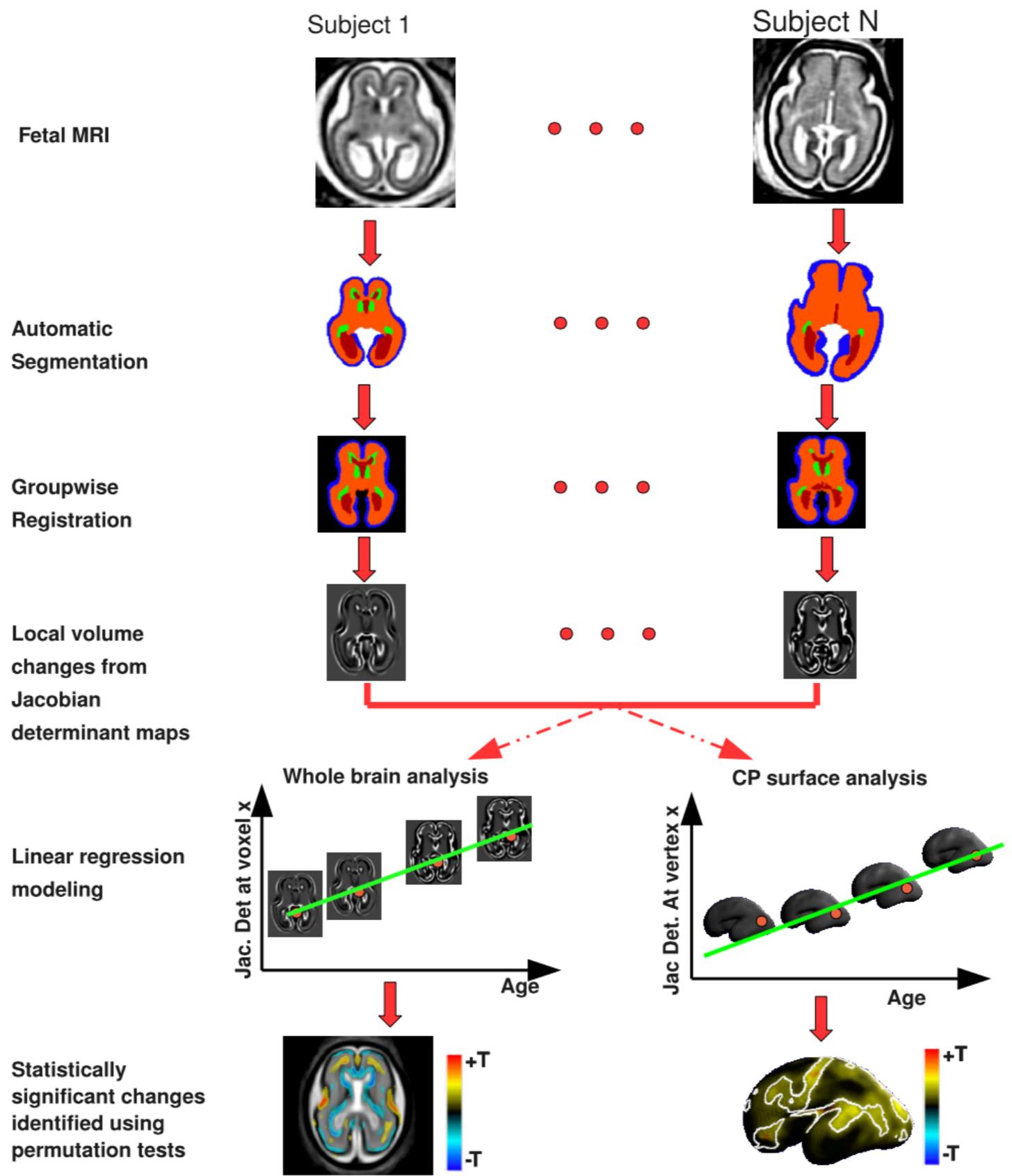
26
semaines



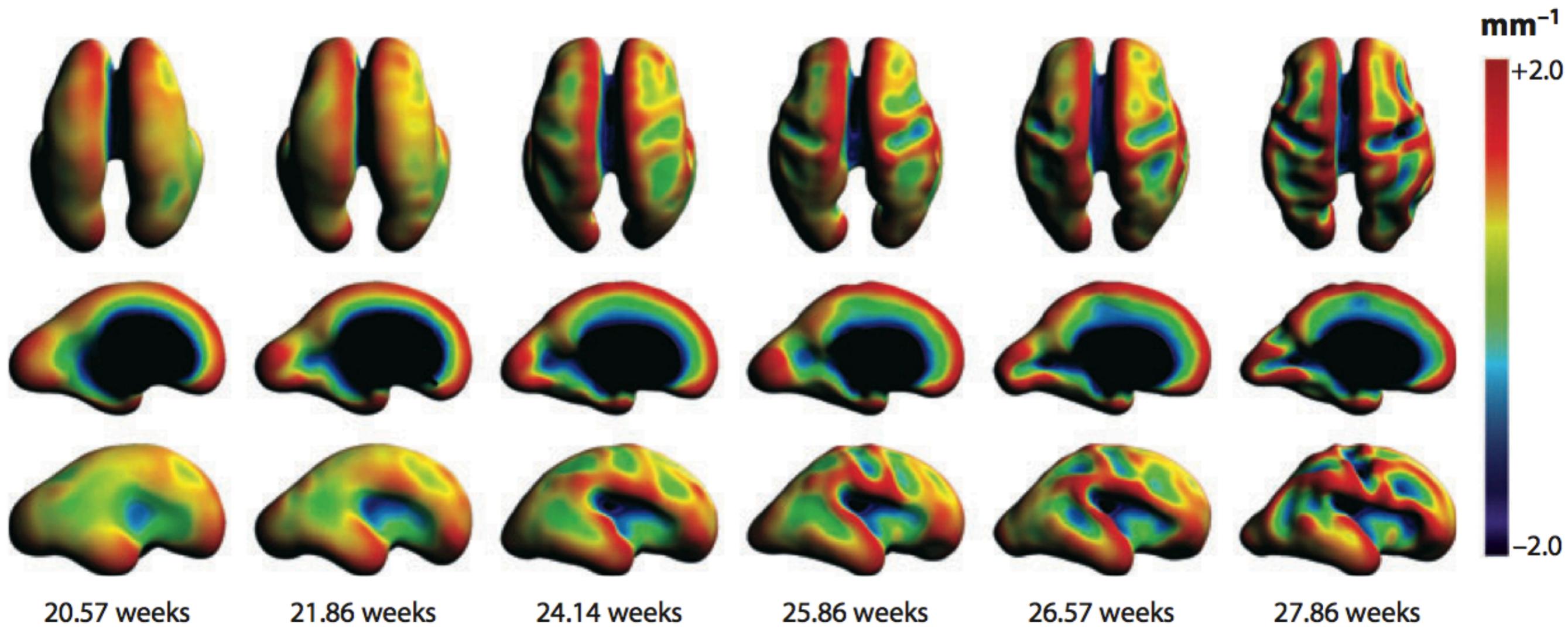
34
semaines



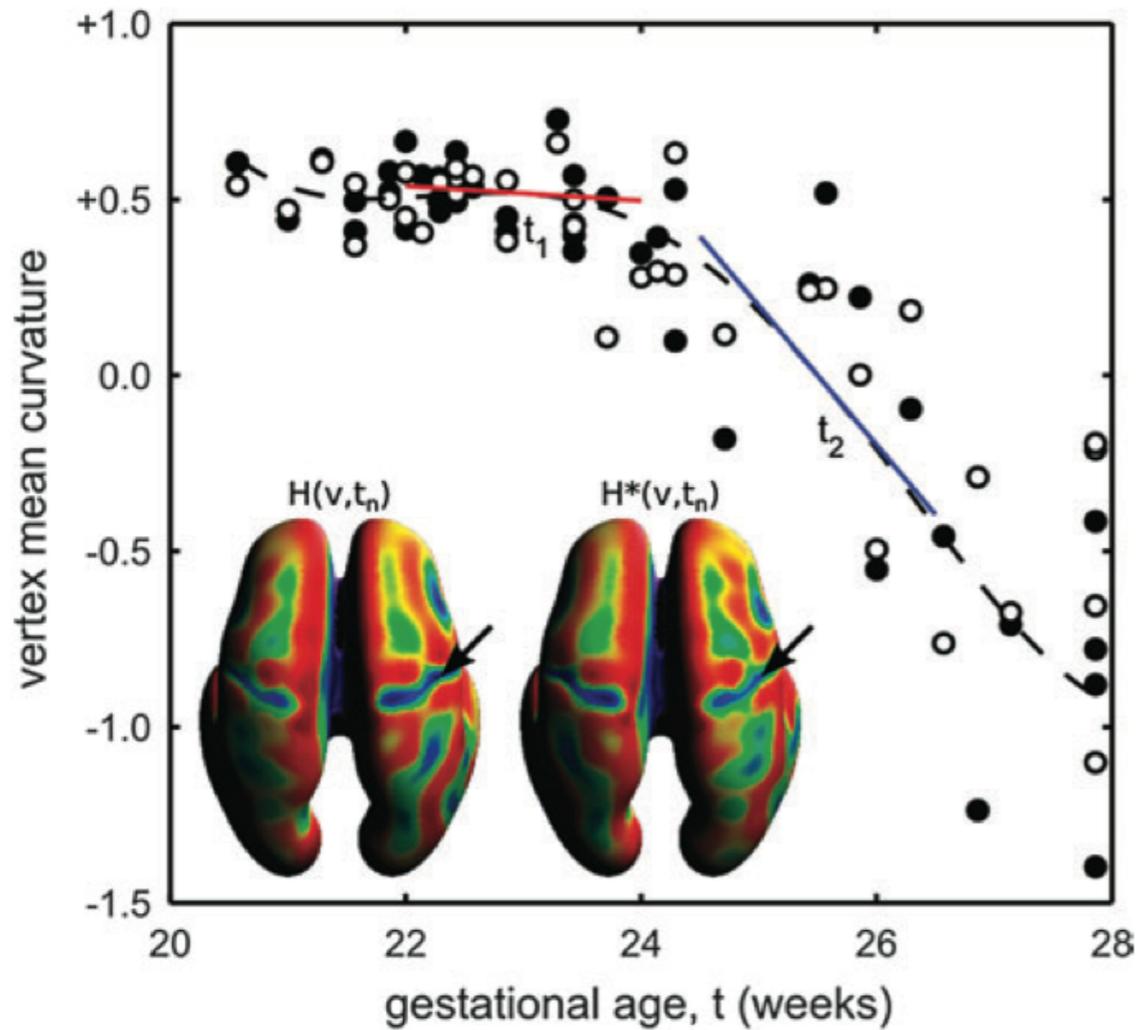
Mise en évidence visuelle de la gyration du cerveau foetal



[Rajagopalan 2011]



[Habas et al. 2012]



analyse de la courbure

approche statistique

calendrier d'apparition des sillons

comparaison post-mortem

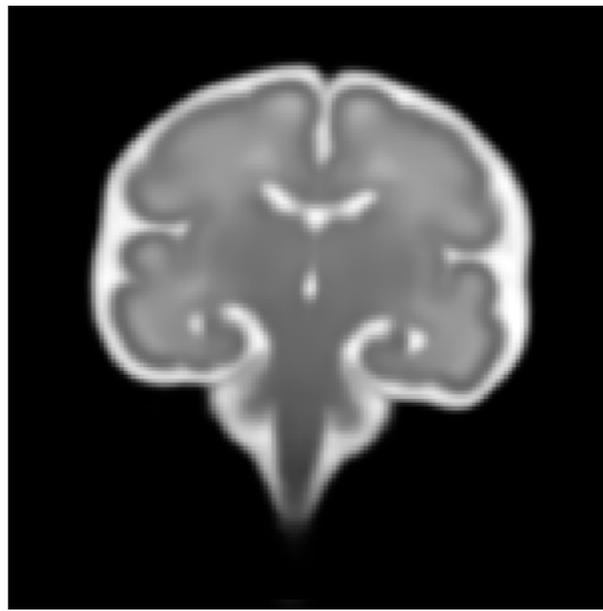
Représentations compactes

ACP

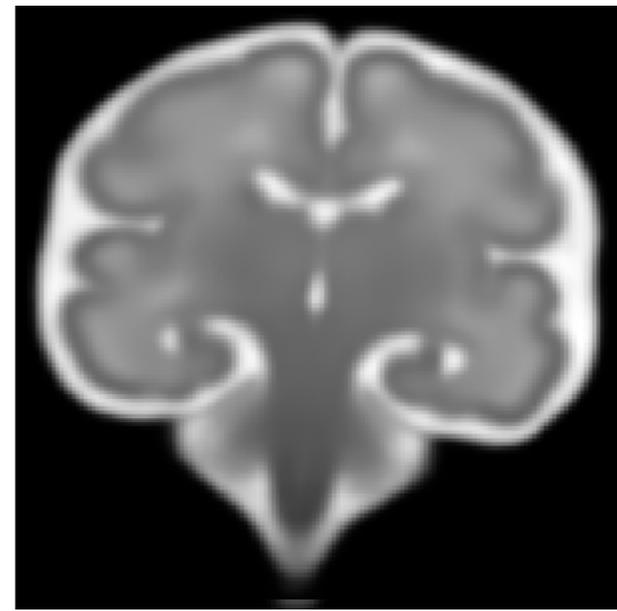
- Transformations affines (6 paramètres)
- Deux modes capturent 99% de la variabilité
- Le premier mode représente 95% de la variabilité



$$-3\sqrt{\lambda_1}\vec{v}_1$$



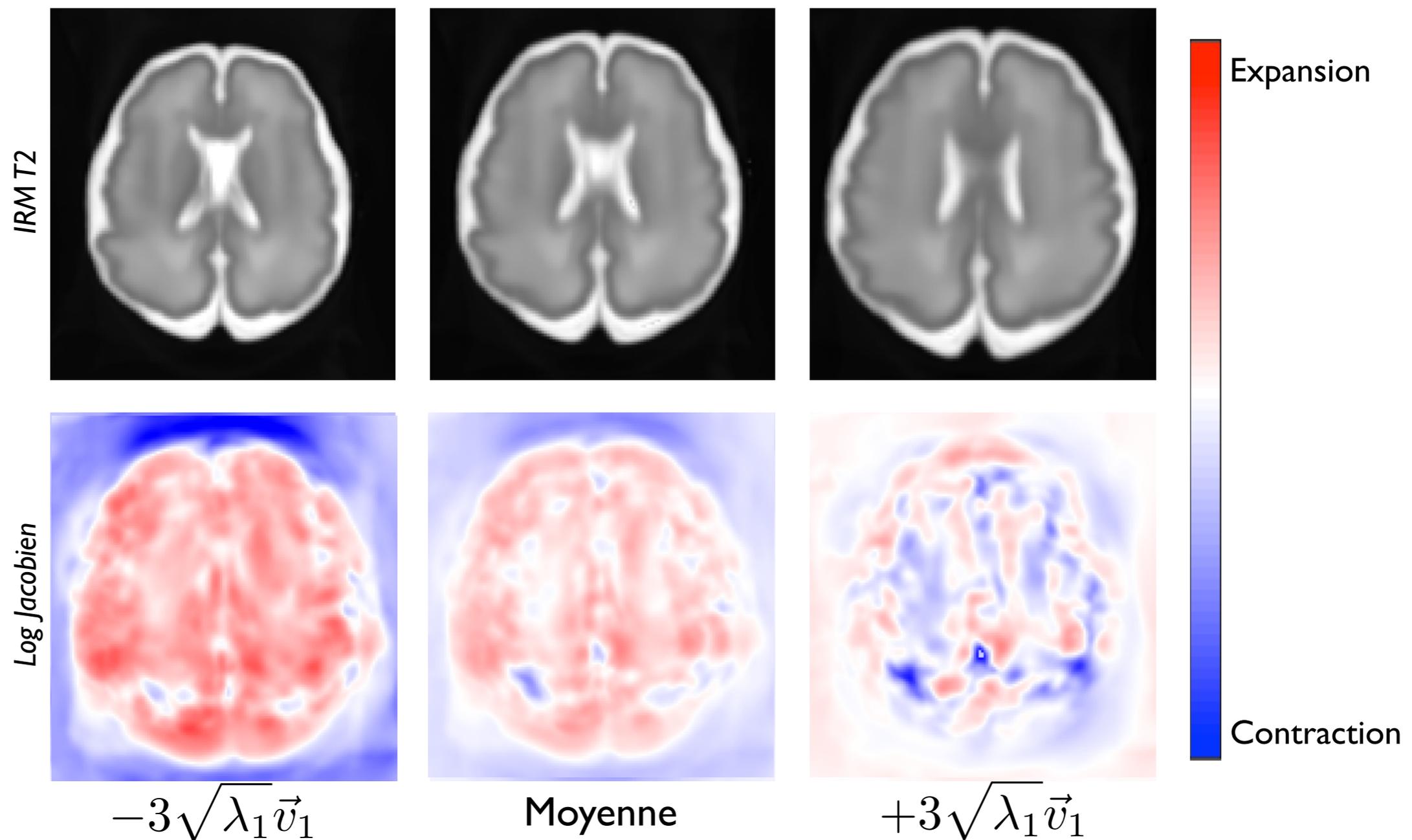
Mode I



$$+3\sqrt{\lambda_1}\vec{v}_1$$

ACP locale

- Champs de déformation ($\sim 1\,000\,000$ de vecteurs)
- 16 modes capturent 99% de la variabilité



Sélection de caractéristiques

$$\mathbf{Y} \in \mathcal{M}_{p \times N} (\mathbb{R}^3) \quad N \ll p$$

N : nombre d'individus

p : nombre de vecteurs de déplacement

Individus

Vecteurs

$$\left(\begin{array}{cccccc} y_{11} & y_{12} & \cdots & y_{1i} & \cdots & y_{1N} \\ y_{21} & y_{22} & \cdots & y_{2i} & \cdots & y_{2N} \\ \vdots & \vdots & \ddots & y_{ji} & \ddots & \vdots \\ y_{p1} & y_{p2} & \cdots & y_{pi} & \cdots & y_{pN} \end{array} \right) \quad \mathbf{X} \subset \mathbf{Y}$$

$$Y_i = f(X_i) + \epsilon_i$$

- Transformations locales

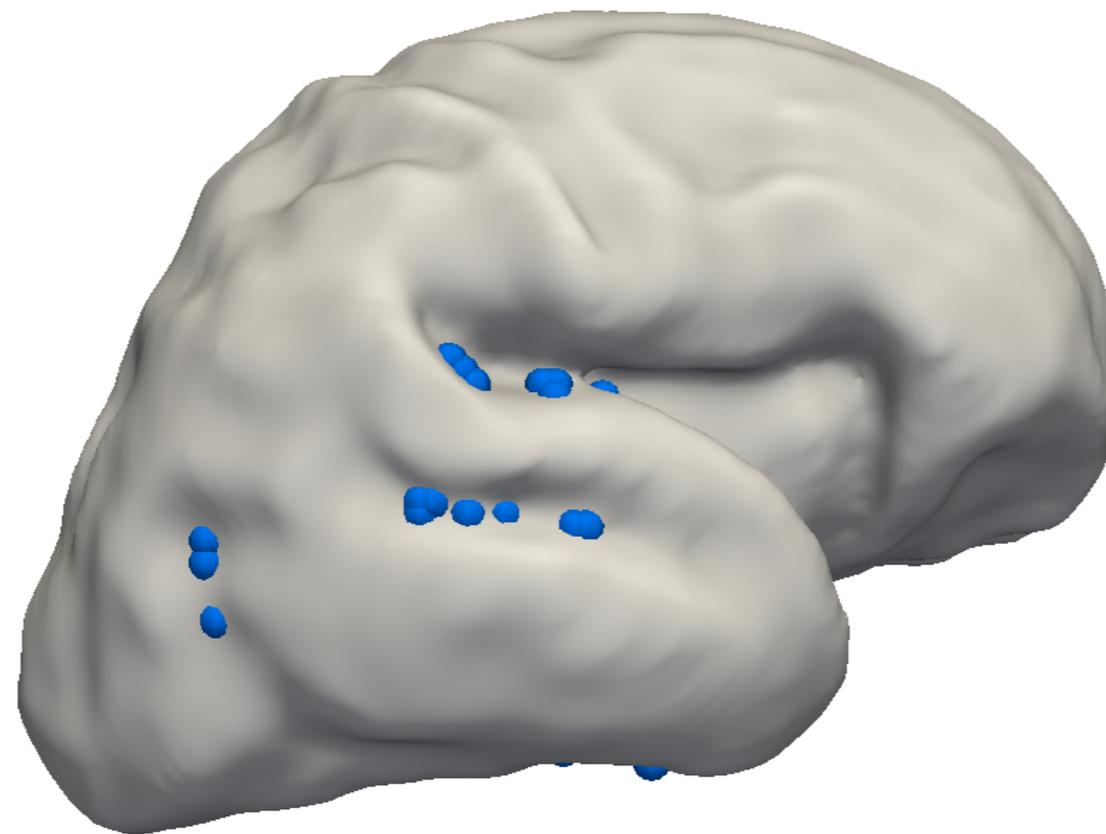
$$\mathbf{Y} \in \mathcal{M}_{p \times N}(\mathbb{R}^3)$$

- Modélisation non-paramétrique à noyaux

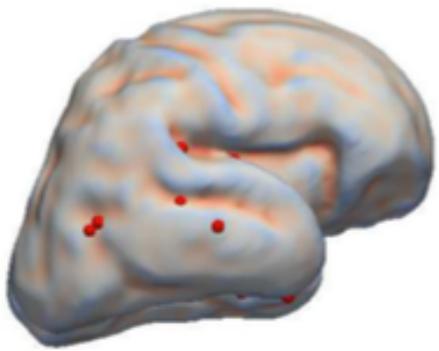
$$\hat{f}(X) = \sum_{i=1}^N w_i(X) Y_i$$

- Minimisation de l'erreur de reconstruction

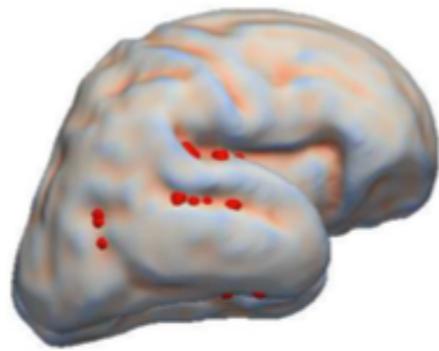
$$\sum_{i=1}^N \|Y_i - \hat{f}(X_i)\|_2^2, \text{ tel que } \|X_i\|_0 = p'$$



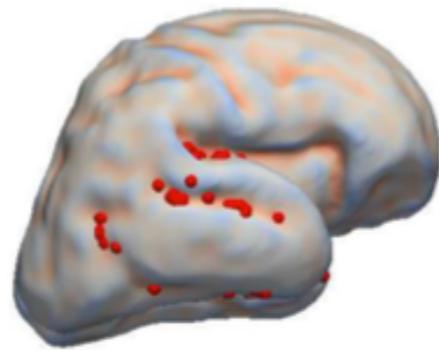
Résultats d'une sélection de points corticaux sur une région
couvrant le lobe temporal droit



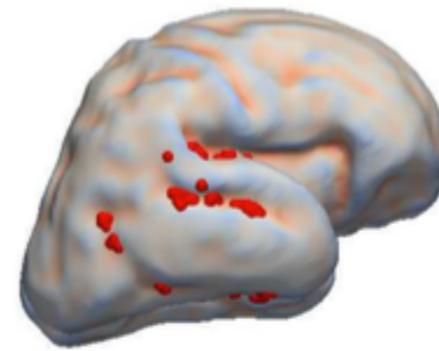
(a) $h = 0.5$



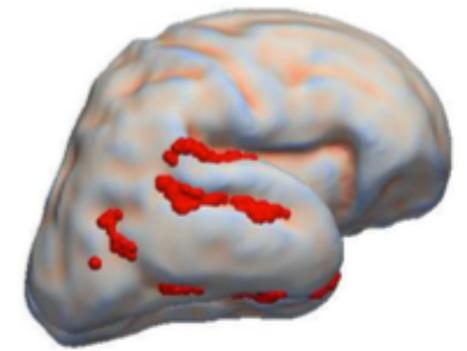
(b) $h = 1$



(c) $h = 1.5$



(d) $h = 2$



(e) $h = 3$

analysis of bandwidth parameter influence

Conclusion

- Morphométrie : étude des formes
- Construction d'un atlas temporel
- Estimation de motifs temporels d'intérêt
- Application à l'étude du développement cérébral

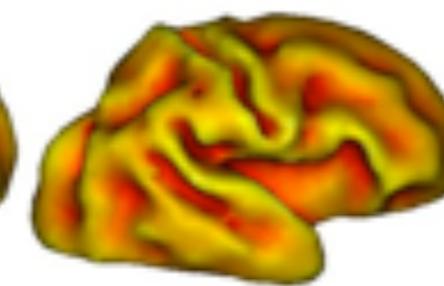
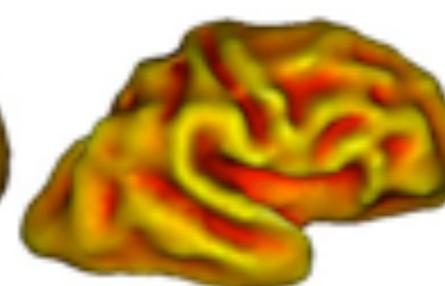
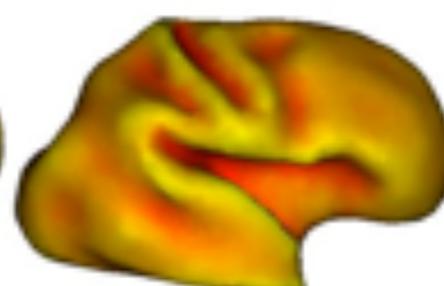
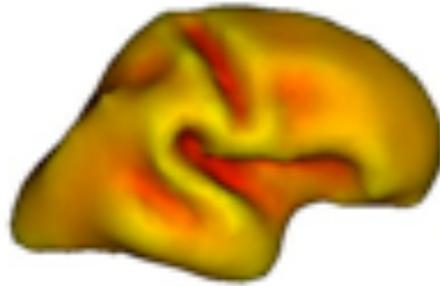
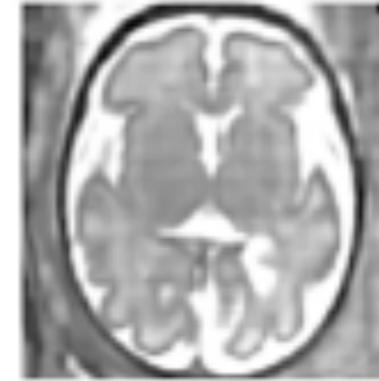
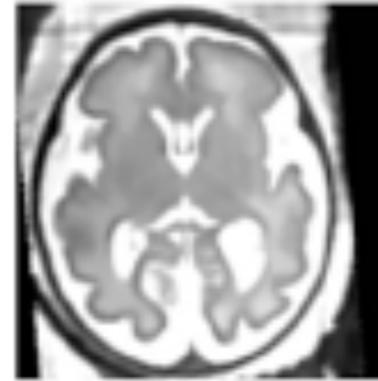
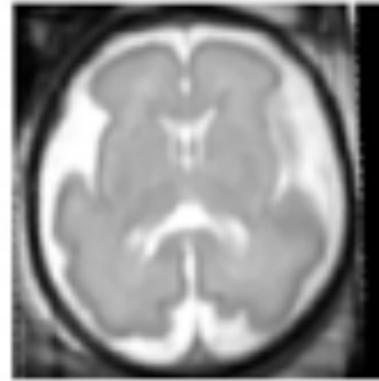
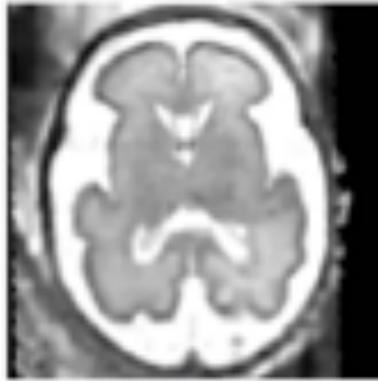
Fetuses

28w GA

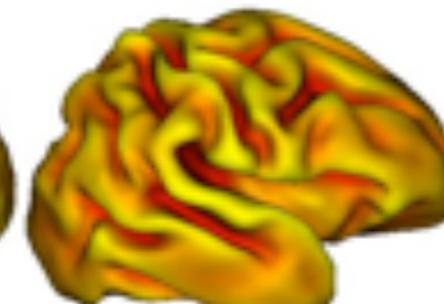
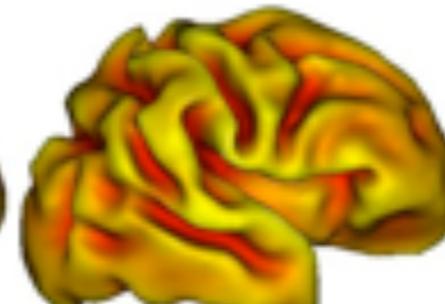
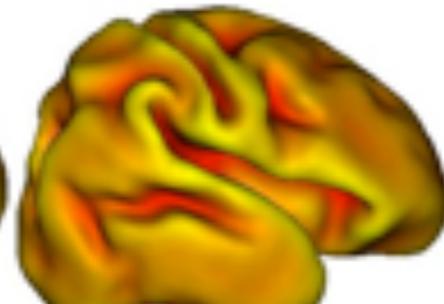
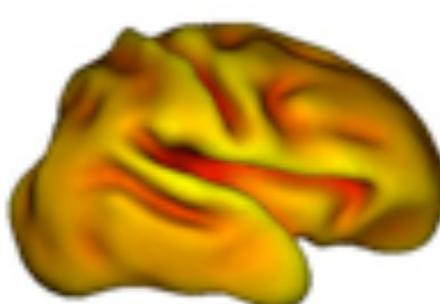
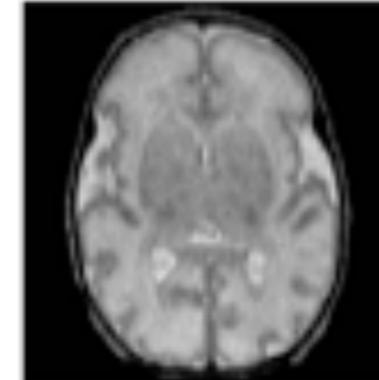
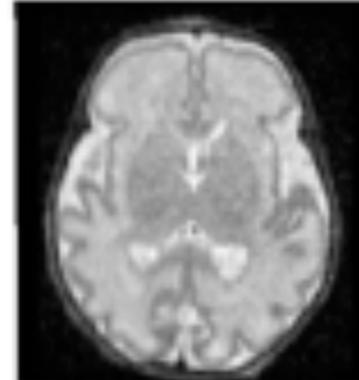
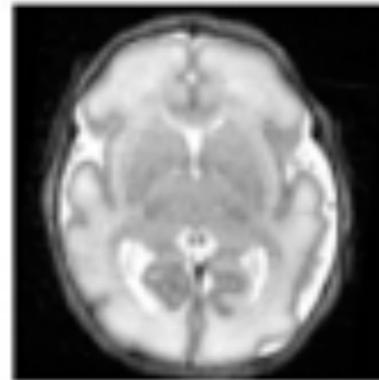
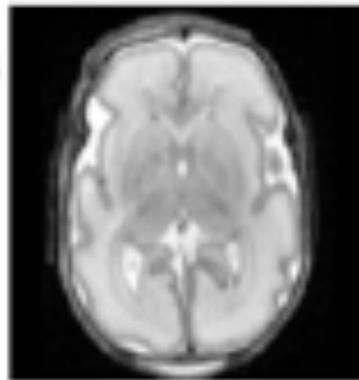
30w GA

32w GA

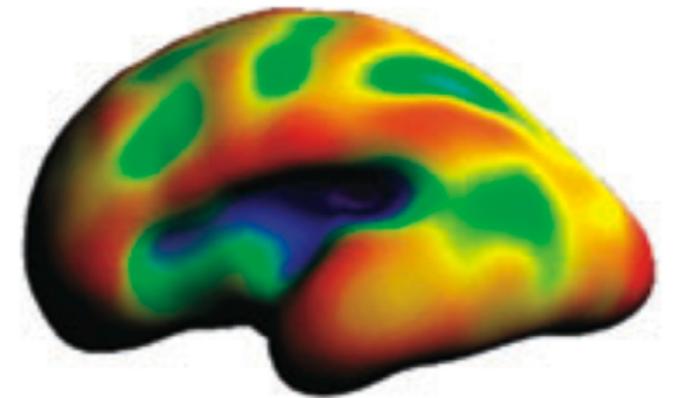
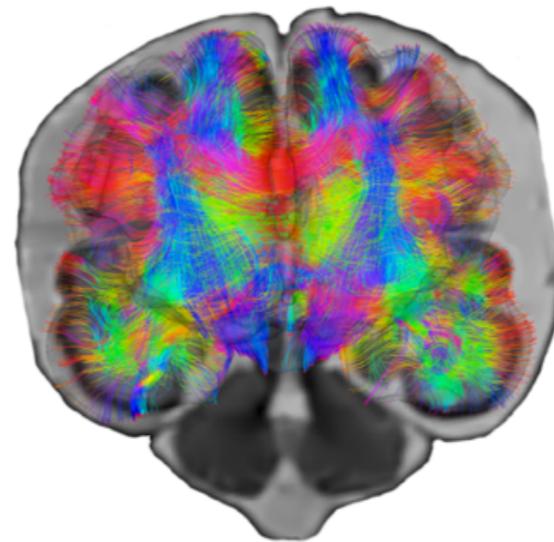
33w GA



Preterm newborns



Etude morphométrique du développement cérébral in utero à partir d'IRM



François Rousseau

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