Doctoral School
ED184

Computer Science - Mathematics

Size-controlled Sulcal Depth estimation

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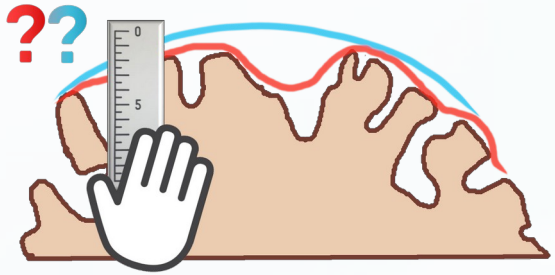


How deep is your brain ?

Introduction

Sulcal depth is a relevant descriptor and morphological feature to study :

- Methodological applications
- clinical applications

- exemples of methodological application : **Registration**
  - (Robinson et al.,2017) Multimodal Surface Matching with Higher-Order Smoothness Constraints -> use of sulcal depth
  - (Fischl, 2012) FreeSurfer -> registration based on SULC : sulcal depth estimation
  - (Lyttelton et al.,2007) An unbiased iterative group registration template for cortical surface analysis -> based on sulcal depth

- exemples of **clinical applications** :
  - (Li et al., 2021) Atypical sulcal pattern in boys with attention-deficit/hyperactivity disorder
  - (Asschenfeldt et al., 2021) Abnormal Left-Hemispheric Sulcal Patterns in Adults With Simple Congenital Heart Defects Repaired in Childhood
  - (Clouchoux et al.,2013) Delayed Cortical Development in Fetuses with Complex Congenital Heart Disease

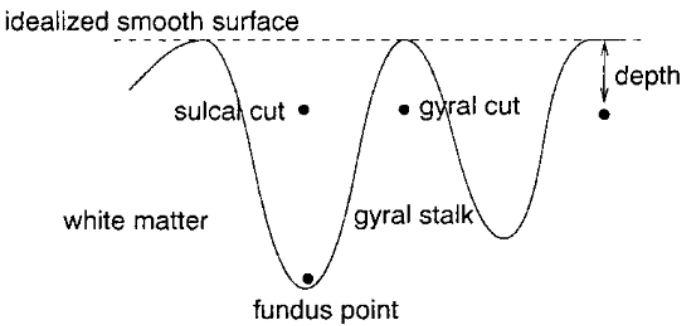
- exemples of methodological application/ **descriptiv surface development**
  - (Bodin et al., 2021) Plis de passage in the superior temporal sulcus: Morphology and local connectivity
  - (Leguen et al., 2018) Genetic Influence on the Sulcal Pits: On the Origin of the First Cortical Folds
  - (Auzias et al.,2015) Deep sulcal landmarks: Algorithmic and conceptual improvements in the definition and extraction of sulcal pits
  - ajouter im

►The choice of sulcal depth method is critical for registration methods, clinical applications and description of the surface.

Introduction

- the intuition is simple, but practically not so easy : no clear definition
- top and bottom of fold : anatomical concepts
- no unique and formal geometric definitions for : gyri, fundi, wallpinches, valley, ridges ...

simple intuition

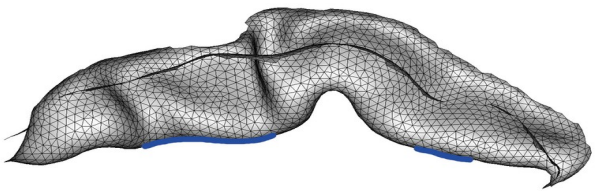


(Lohman et.al, 1998)

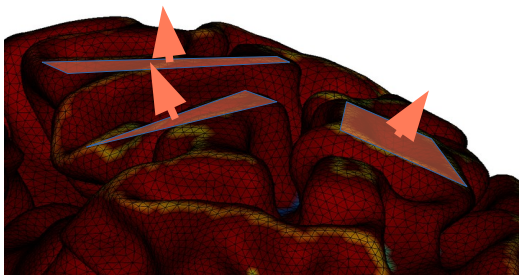
we want a reliable numeric method

OPEN QUESTION

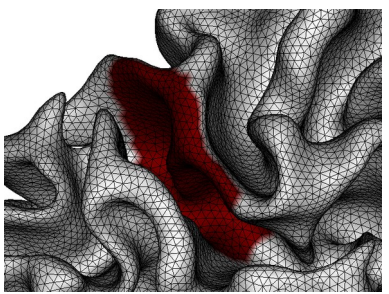
complex sulcal bassin

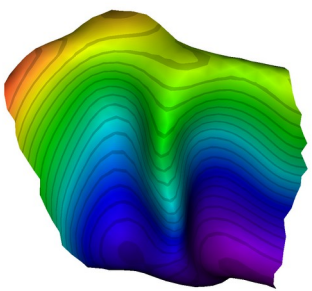


no clear extrema



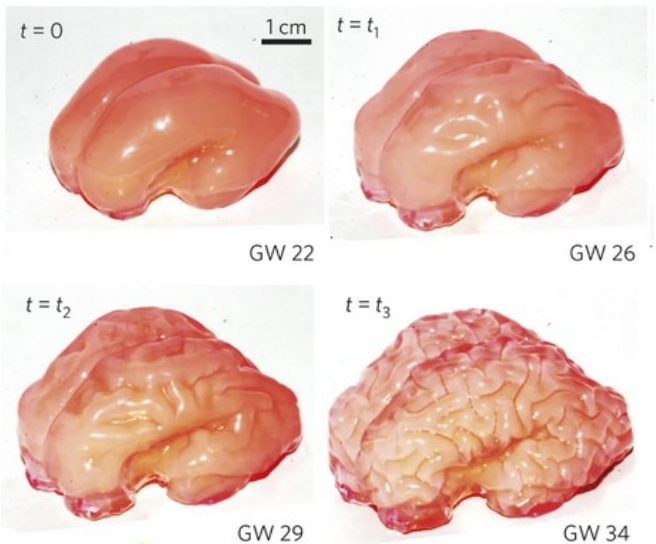
3D folding : buried gyri, Wallpinches ..



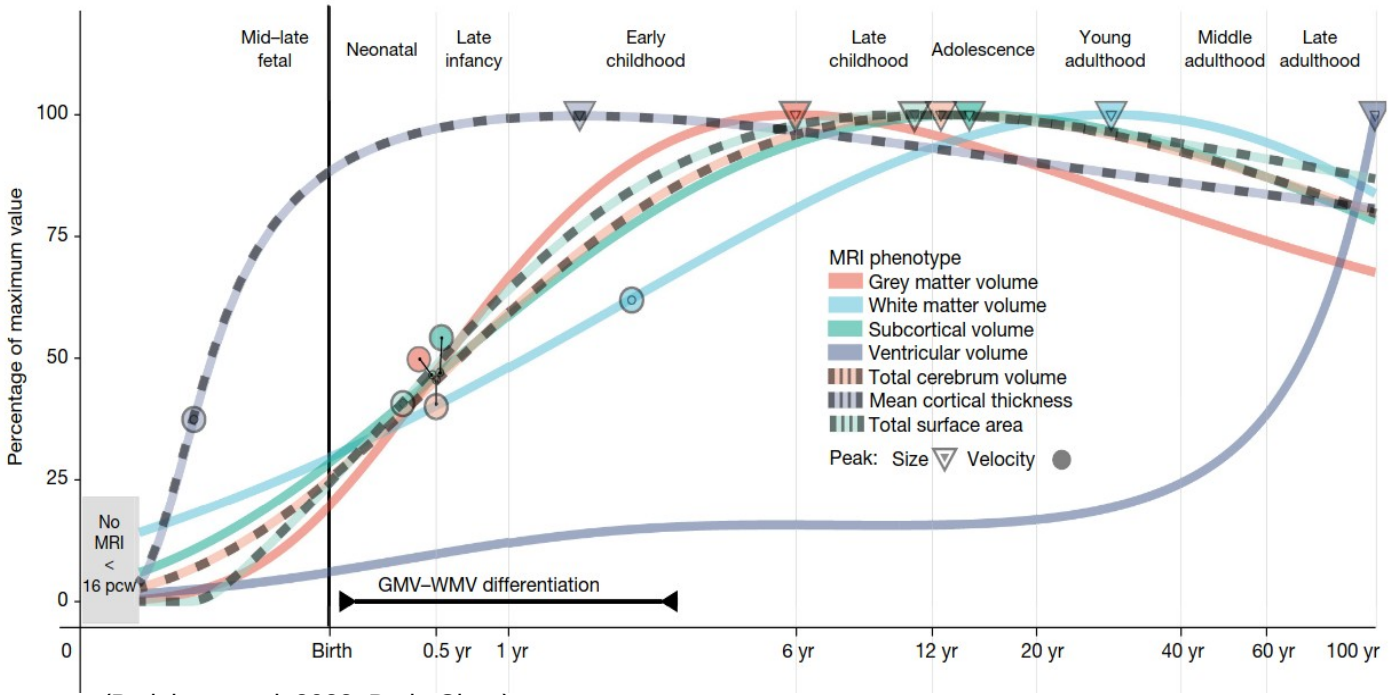


Introduction

The folds and size change with age



(Tallinen et.al, 2016)



(Betlehem et.al, 2022, Brain Chart)

methods impact clinical results

Summary

1. What are the differents sulcal depth estimation methods ?

- Distance-based methods and their limits
- Diffusion-based methods and their limits

2. How to evaluate the differents methods ?

- The methods are differents
- The differences impact your application
- Litterature : evaluation with clinical applications
- Contribution : a framework for evaluate depth methods

3. How to deal with size variations of the brain ?

- Litterature : different methods for differents size
- Contribution : a unique size-controled method

1. What are the differents sulcal depth estimation methods ?

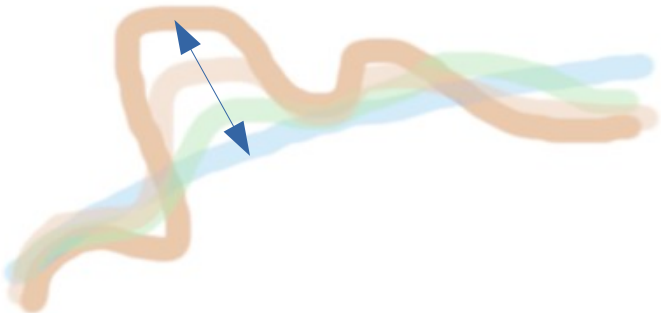
2. How to evaluate the differents methods ?

3. How deal with size variations ?

Distance-based methods

►Sulcal depth is the distance relative to an external surface

Diffusion-based methods



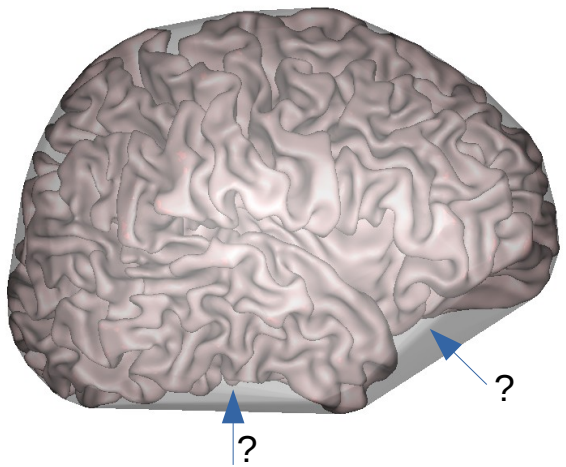
►Sulcal depth is estimated by a diffusion process

1.The differents methods for sulcal depth estimations : distance-based

You need :

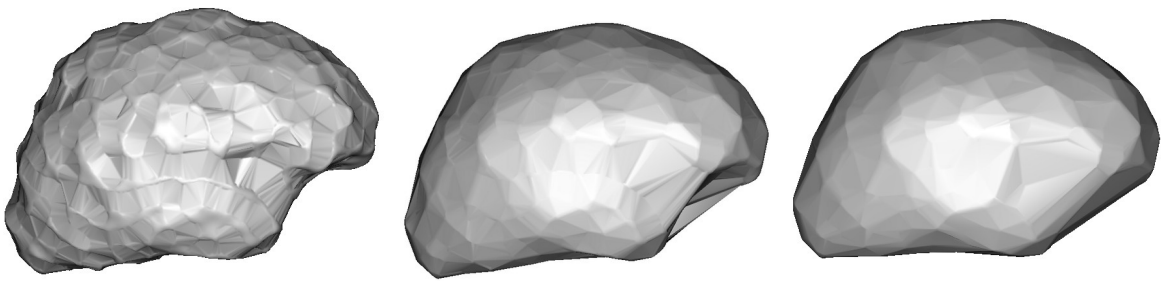
- **a distance definition** : Euclidean, Geodesic or Adaptative
- **an external surface** : Convex-hull or Alpha-shape/ Wrapper-surface

Convex-Hull



- unique definition
- but brain shape is not convex

Wrapper-Surface



- adaptative to the convex/concav shape
- but no unique definition
- create artefacts
- require pre and post processings steps (smoothing, cleaning...)

1.The differents methods for sulcal depth estimations : distance-based

You need :

- **a distance definition** : Euclidean, Geodesic or Adaptative
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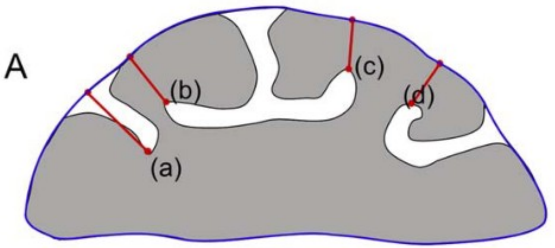
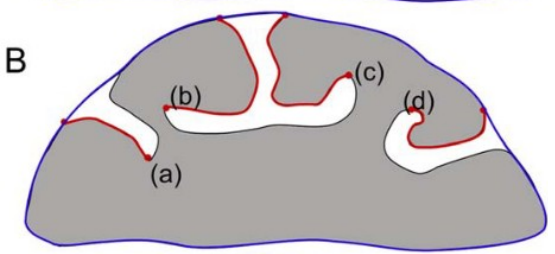
Euclidean distance



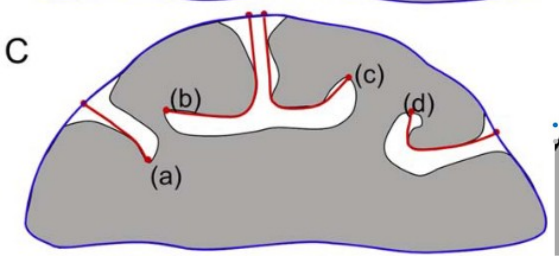
- underestimated high convoluted folds

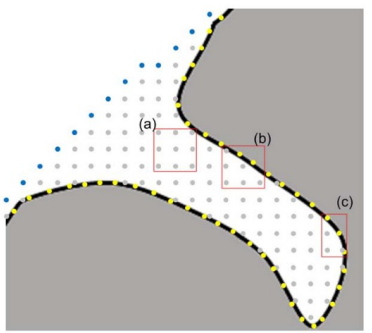
Geodesic distance



- overestimated shallow bassins

Adaptativ distance



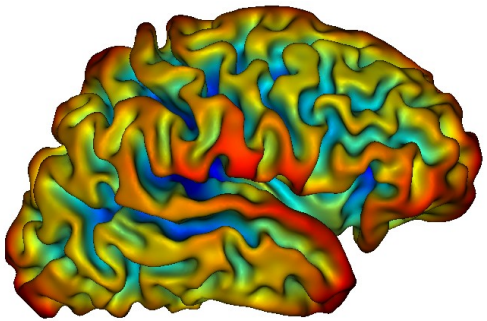


- good alternative
- need to discretised the inbetween space
- noise sensitiv

(Yun et.al, 2013)

1.The differents methods for sulcal depth estimations : diffusion-based

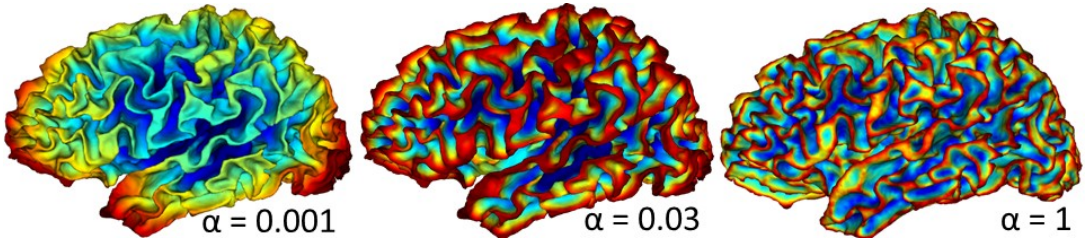
Sulc



from Freesurfer pipeline

(Fischl et.al, 2002)

Depth potential function

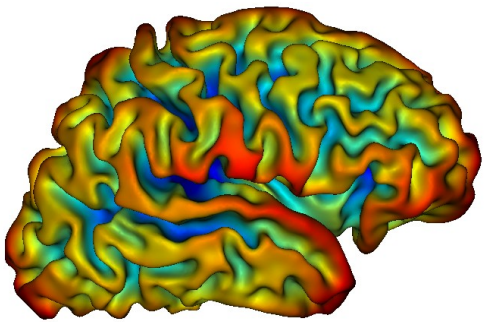


based on a screened Poisson equation $\left(\alpha.I + \Delta_M \right) D_\alpha = K$

facteur d'échelle laplacien profondeur courbure

(Boucher et.al, 2009)

Sulc



from Freesurfer pipeline

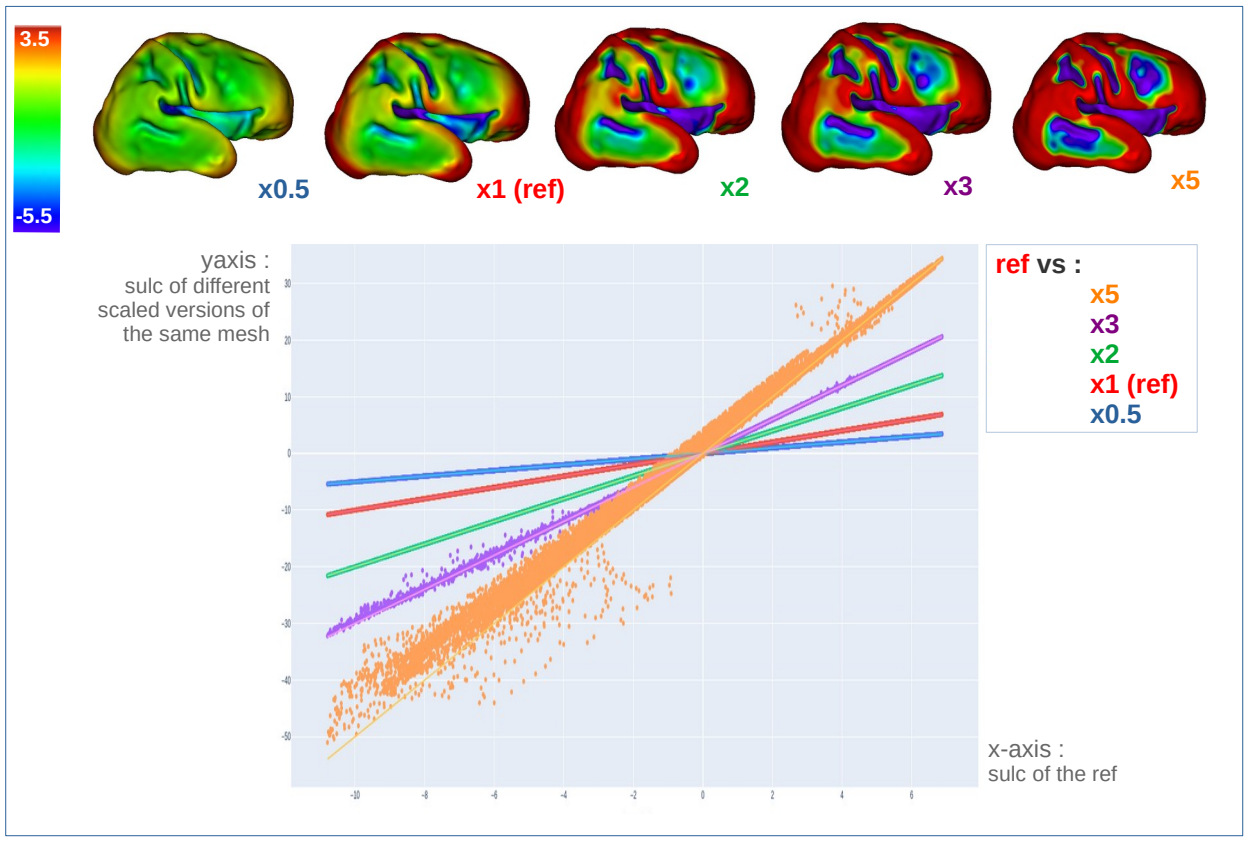
- Depth is the distance travelled by each point during an inflation transformation of the mesh.

- kind of black-box, ready to use
- a lot of parameters and hyper parameters set by default

- method used a lot ! because easy to use.

- not robust to isometric scaling
- global and local inconsistencies for individual subject

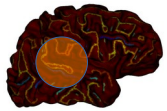
Not size invariant : not robust to isometric scaling

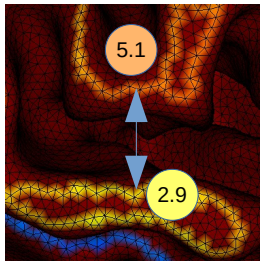


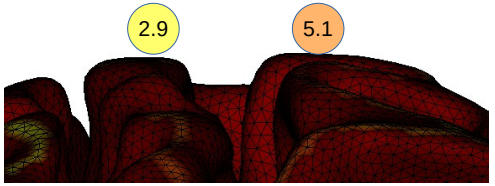
1.The differents methods for sulcal depth estimations : diffusion-based: SULC

Crest-to-crest inconsistencies

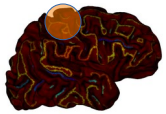
On either side of the sylvian fissure

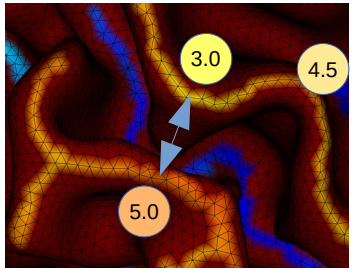


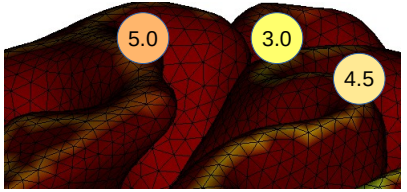




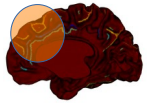
On either side of the central sulci

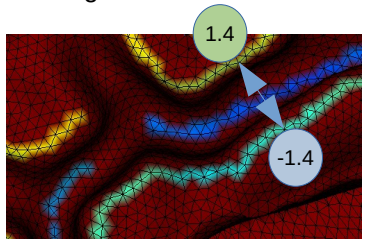


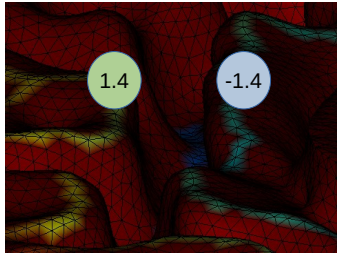




On either side of the cingulate

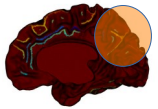


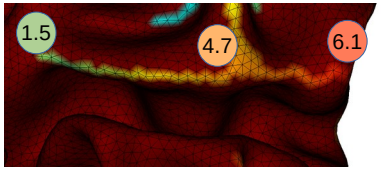


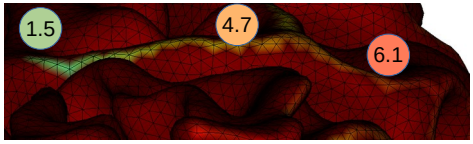


Inconsistencies along a same crest

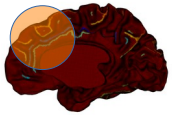
Along the parieto-occipital sulci

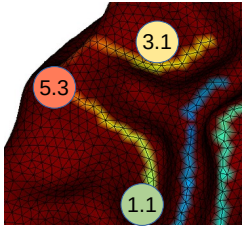


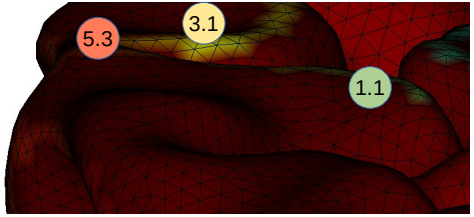




along the crests of the medial frontal cortex

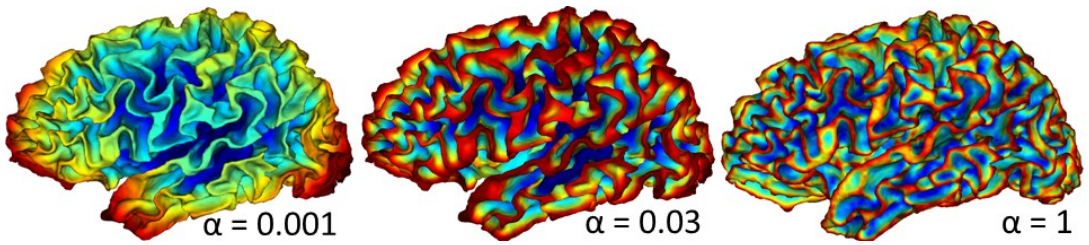






The differents methods for sulcal depth estimations : diffusion-based : DPF

the depth potential function



α : screened coeficient $[\alpha] \equiv L^{-2}$

I : Identity matrix

Δ_M : Mesh laplacian $[\Delta_M] \equiv L^{-2}$

K : Mesh mean Curvature $[K] \equiv L^{-1}$

D_α : The DPF $[D_\alpha] \equiv L$

based on a screened Poisson equation :

$$(\alpha.I + \Delta_M)D_\alpha = K$$

scale control — Laplacian — Depth — Curvature

~ratio between curvature and concavity

~variation of bending

~bending

(Boucher et.al, 2009)

The differents methods for sulcal depth estimations : Recap

Euclidean	- size-dependant external surface - underestimate convoluted bassins	intuitive
Geodesic	- size-dependant external surface - overestimated shallow bassins	
Adaptativ	- size-dependant extern surface - size-dependant discretisation inbetween surface	
Sulc	- size dependant - influence of high-concavity regions - local crest to crest inconsistencies - global crest to fundi inconsistencies	ready to use
DPF	- size dependant - empirical setting	- visually promising - no external surface - scale parameter

1. What are the differents sulcal depth estimation methods ?

2. How to evaluate the differents methods ?

3. How deal with size variations ?

2. Evaluate the sulcal depth methods : comparaison

Distance-based method comparaison value comparaison

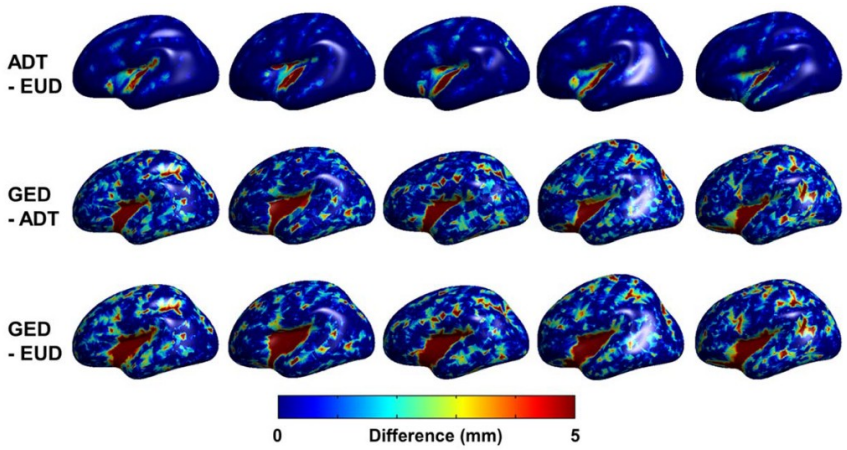
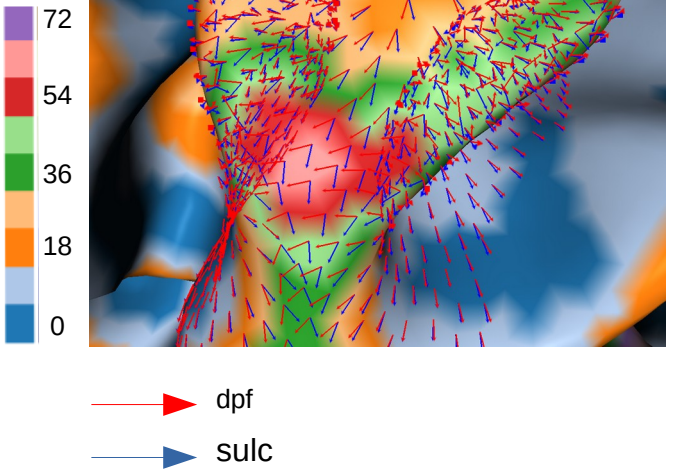
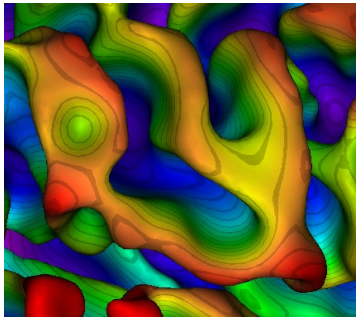
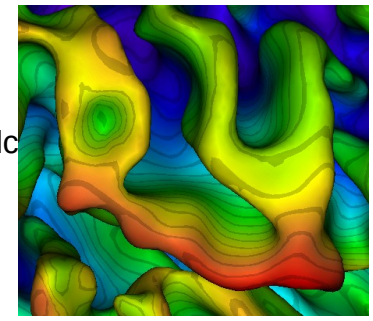


Figure 6. An example of the differences among the algorithms in the 5 subjects.
doi:10.1371/journal.pone.0055977.g006

Diffusion-based method comparaison gradient comparaison





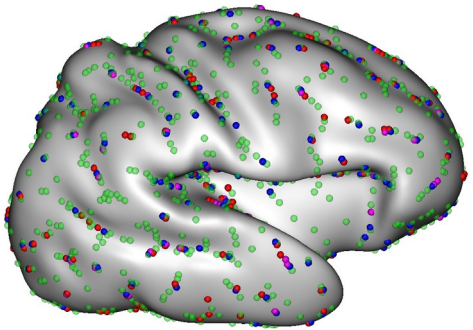


2. Evaluate the sulcal depth methods : comparaison

The difference between methods give **a different interpretation of the surface**.

for exemple :

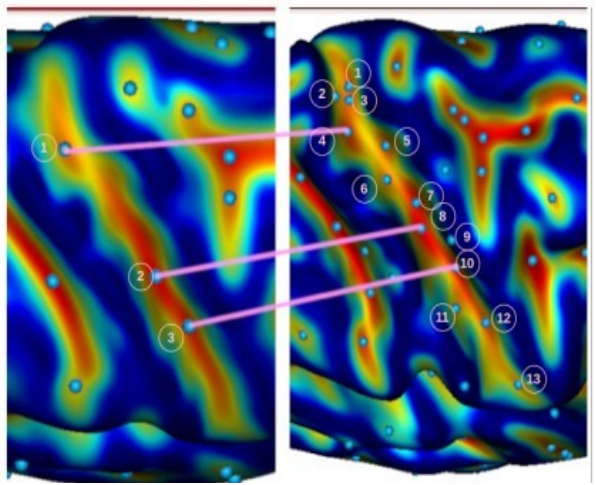
- different scale space



- extrema DPF star , alpha_ref = 0.03, area_ref = KKI113
- extrema DPF basic, alpha = 0.03
- extrema sulc dHCP
- extrema Rusinkievich curv

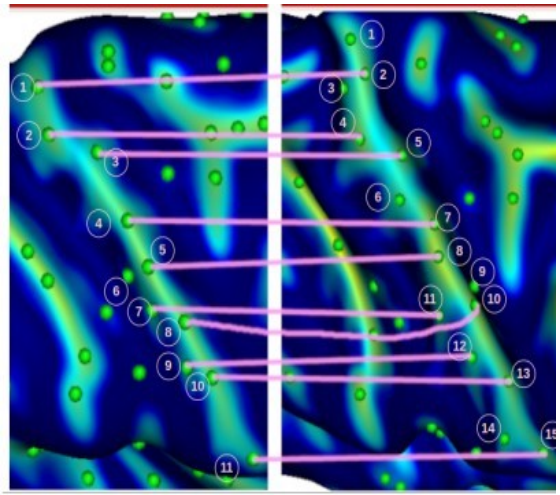
- different spatio temporal emergence of fold :

longitudinal data



dpf setting 1

longitudinal data

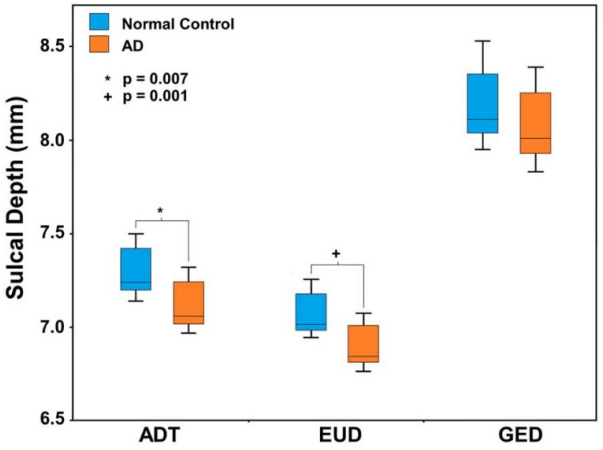


dpf setting 2

2. Evaluate the sulcal depth methods : evaluation in litterature

So far, Methods are evaluate with a clinical application

(Yun et.al, 2013)



Limitations of the actual evaluations:

- Evaluate on an average mesh : do not allow evaluation on a single subject.
- Evaluate with application : the application should not evaluate the measure if you don't have a clear ground truth.

►we need a clear framework for evaluate methods individually without using applications

2. Evaluate the sulcal depth methods : contribution : framework

Define a framework for sulcal depth :

explicit assumptions on sulcal depth/ biomechanical model

folds is depletion ?
sulcal roots model ?

Define properties derives from assumptions

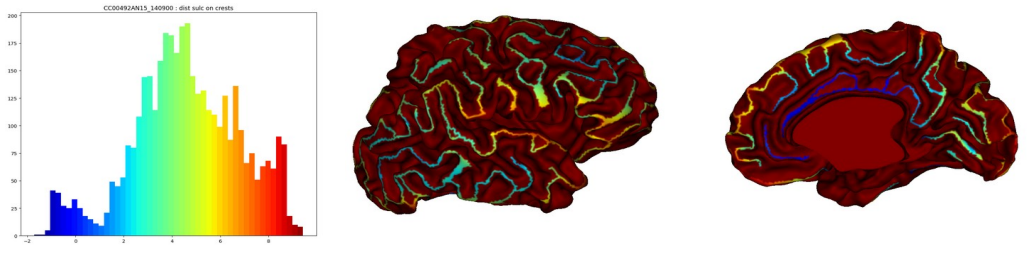
- gyral crest as reference level of depth
- fundi and crest globally seperated
- depth direction goes from crest to fundi

Express quantitative metrics

- ►variance of depth on crest
- ►median difference between crest and fundi depth
- ►angle deviation between gradient and WPs direction

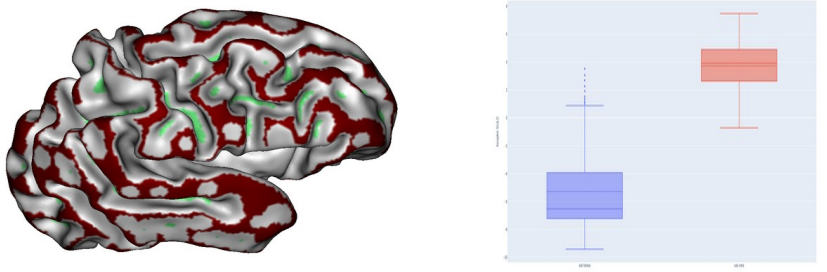
2. Evaluate the sulcal depth methods : contribution : framework

Reference



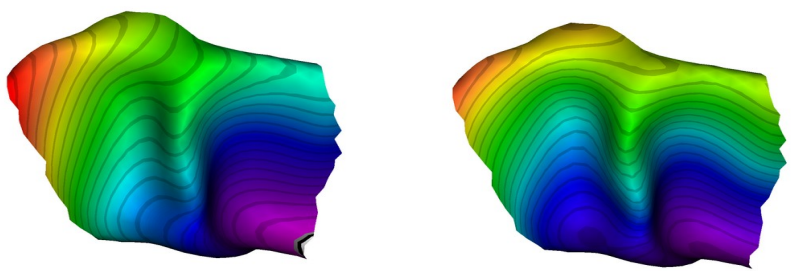
minimise Variance of depth on crest

Separability



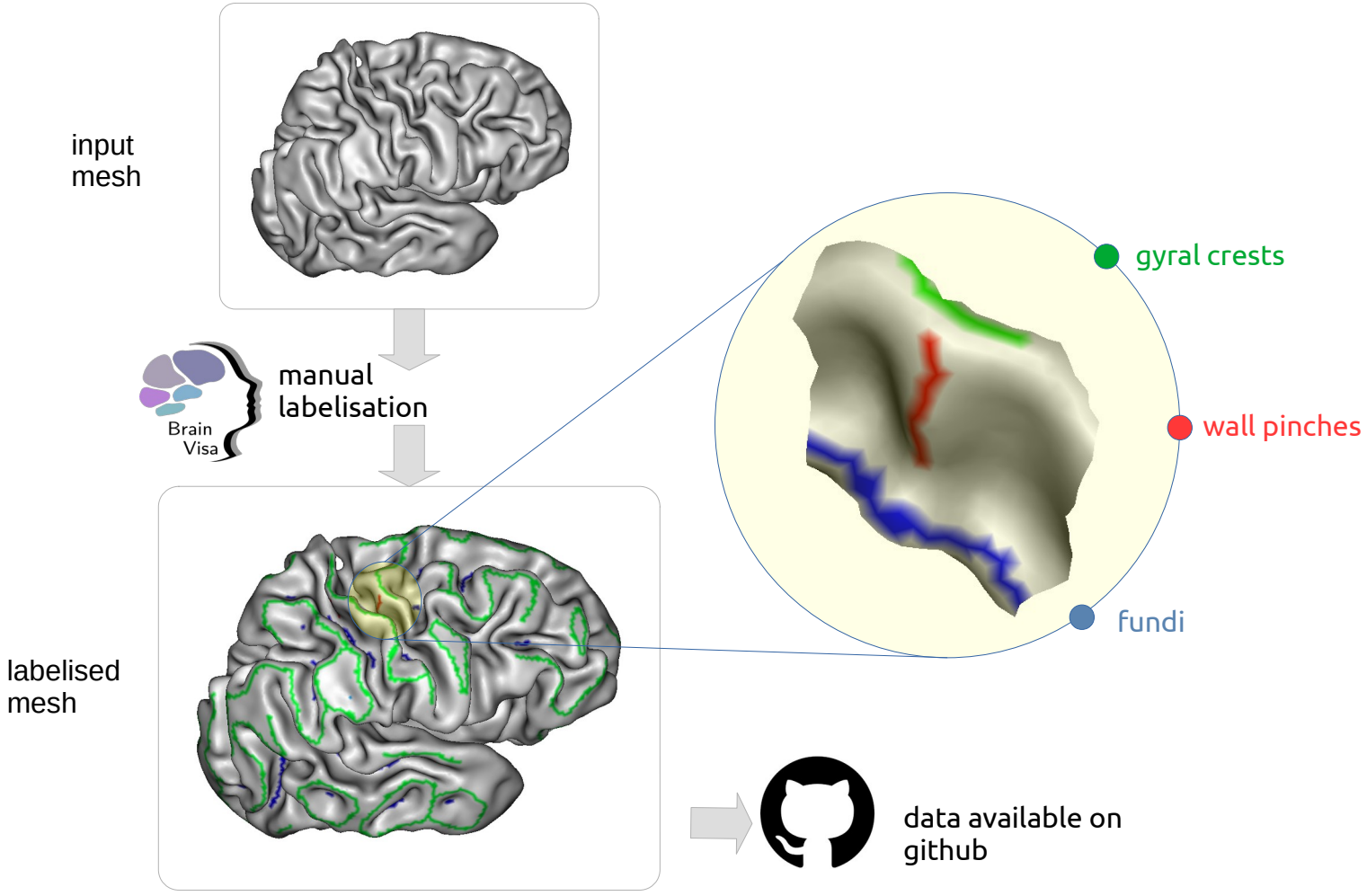
maximise median between crest and fundi depth

Direction



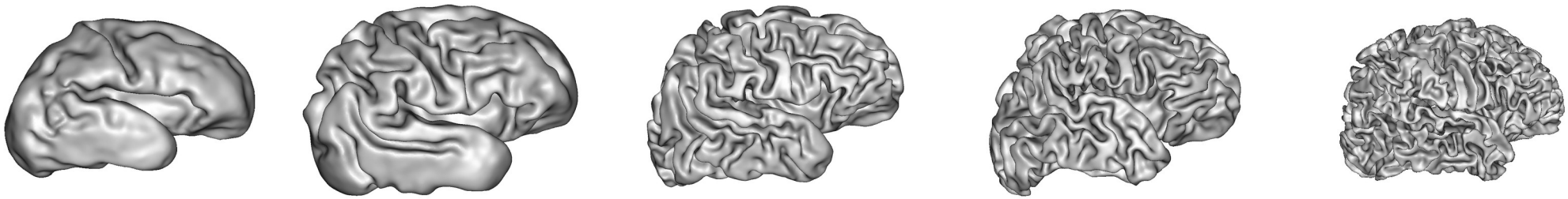
gradient of depth

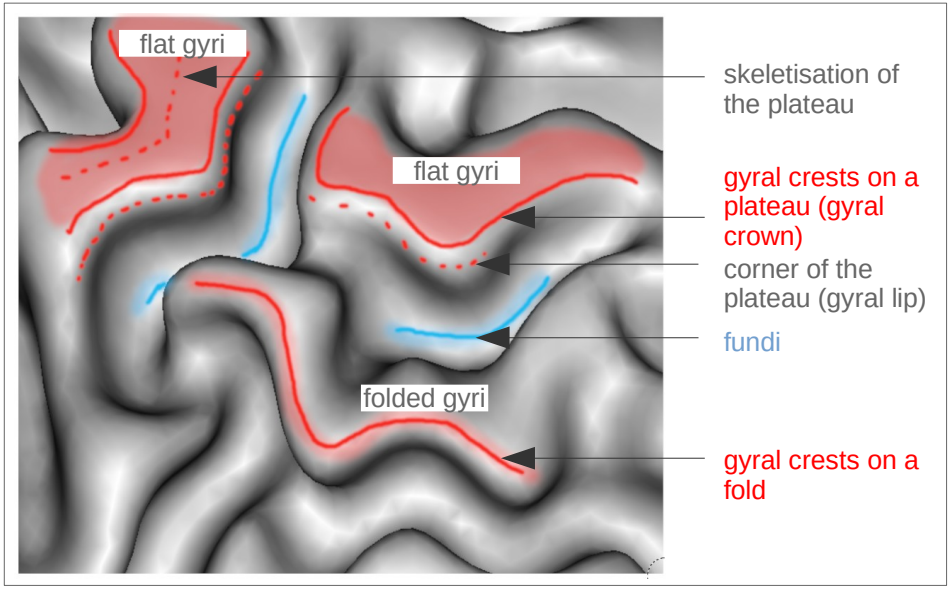
2. Evaluate the sulcal depth methods : contribution : ground truth



2. Evaluate the sulcal depth methods : contribution : ground truth

Tracing protocol : 14 dhcp subjects + KKI adult





- **Conservative criteria**: priority is given to reducing the number of false positives rather than improving the number of good positives.

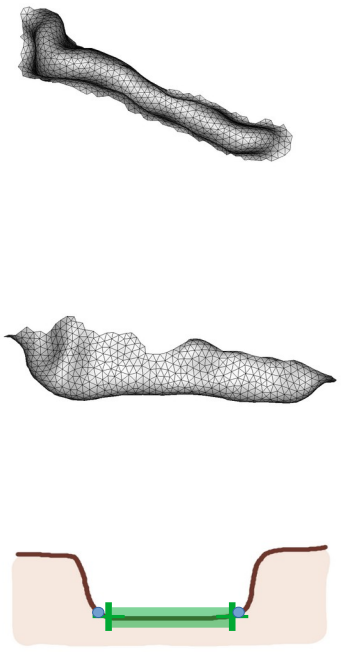
- We define **WPs**, **fundi** and **gyral crests** on a canonical shape of the fold.
- We define the tracing on **variations of the canonical shape**.

- We assess inter-rater reliability.

2. Evaluate the sulcal depth methods : contribution : ground truth

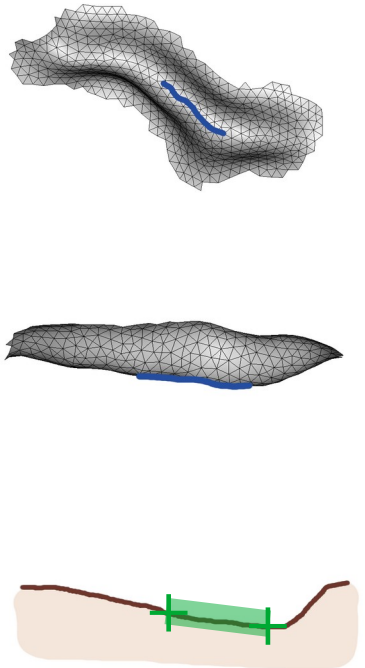
Canonical shape

Aceptable variations



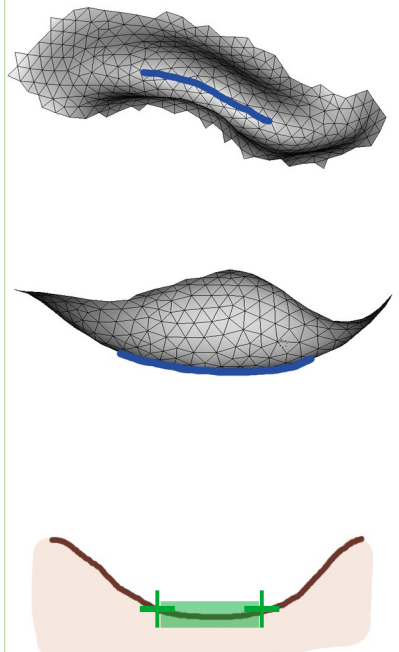
inflexion points

one extremity smooth transition



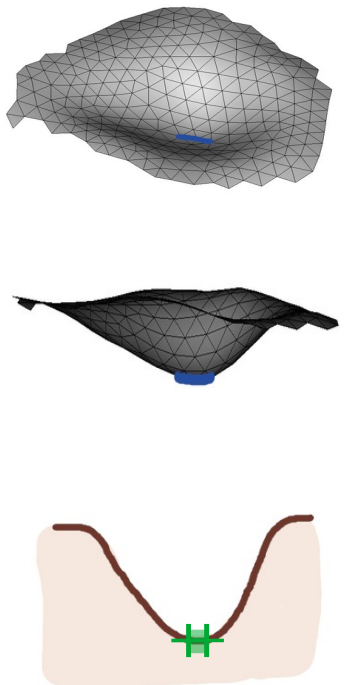
1 inflexions point

U-shape



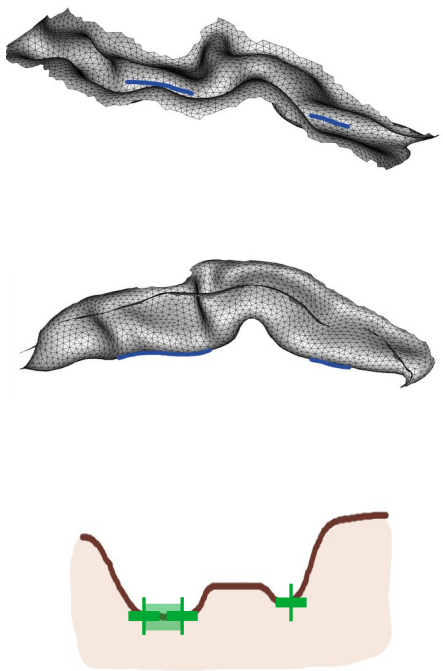
0 inflexions points

Cup-shape



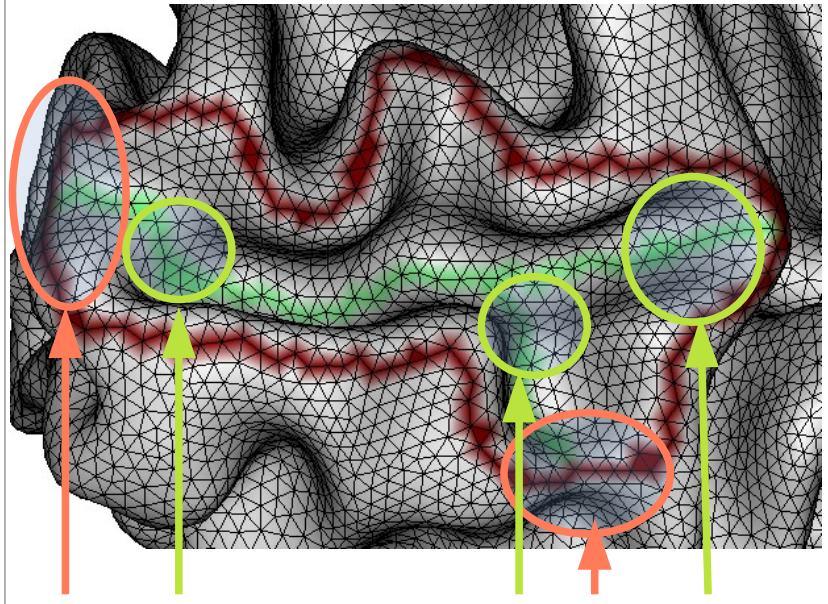
no emergent direction

buried gyri



conservative criteria

Not conservativ labelisation of crests and fundi



open end

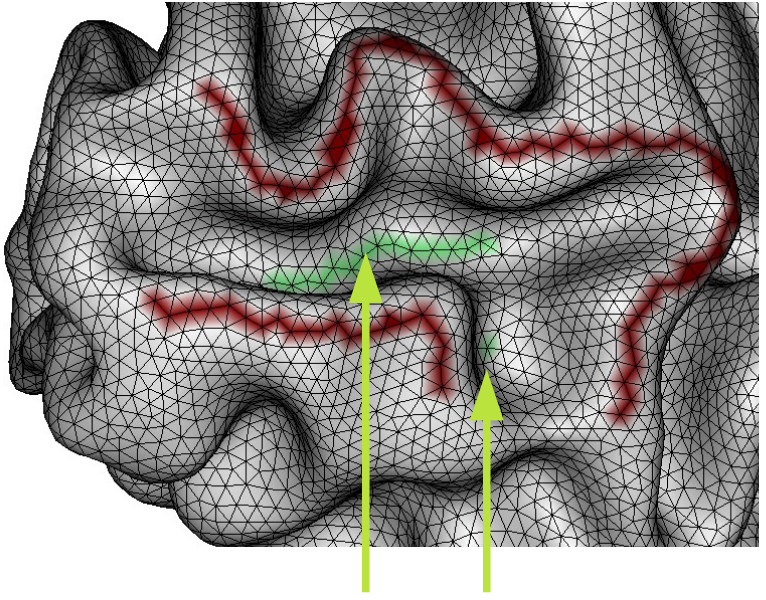
strong variation of curvature

strong variation of curvature

local depletion on the crest

sulcal line on the sulcal wall

Conservativ labelisation of crests and fundi

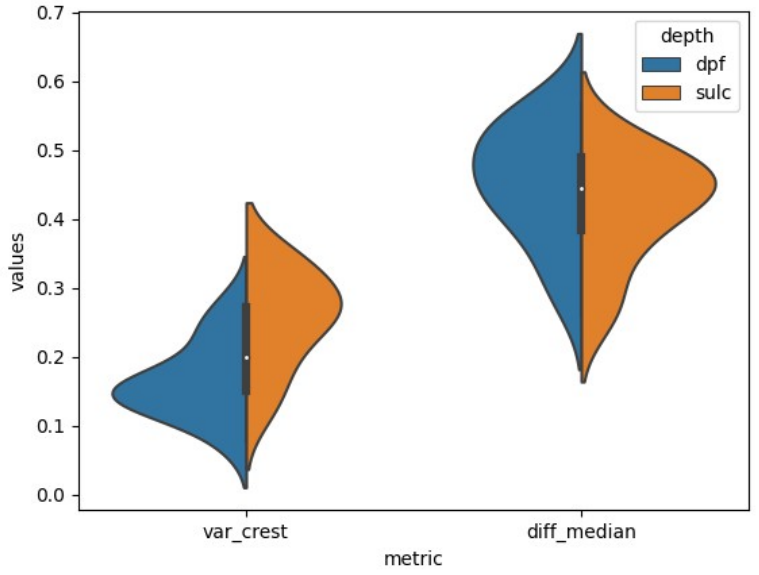


fundi with only slight variations of curvature

local minima

2. Evaluate the sulcal depth methods : contribution : result

comparaison between sulc and DPF with our metrics :



exemple of use :
dpf better than sulc

conclusion :
- initiate common metrics and common framework for evaluate depth
- no need of application
- no need of group analysis
- open data to asses new methods

1. What are the differents sulcal depth estimation methods ?

2. How to evaluate the differents methods ?

3. How deal with size variations ?

3. deal with size variations : litterature

To date, sulcal depth methods are no efficient on young brains

- change methods according the size (ex : curv and apt)
- adapt mannually the methods according size

why this not good :

- artificialy split your data
- need to find an homogeneous space to compare results from different used methods
- circularity of thinking

size independent method is crucial for :

- clarify defintion of depth
- improve reproducibility of results

applications : study on chilhood, neurodevelopemental trajectories, interspecies comparaison ...

3. deal with size variations : contribution : size-controlled DPF

D* is a size independent depth index

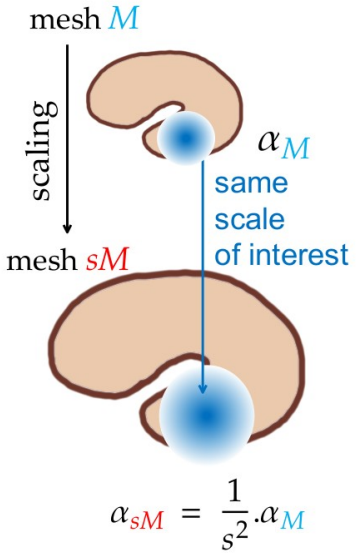
$$D^* = s^{-1} D_{s^{-2}\alpha}$$

normalized Depth scaling Depth scale control

based on the DPF

$$(\alpha.I + \Delta_M) D_\alpha = K$$

scale control Laplacian Depth Curvature



First, we normalize the parameter α to preserve the same scale of interest. Then, we normalise the range of values of the resulting DPF. Proof :

Given the properties of curvature and Laplacian

$K_{sM} = \frac{1}{s}.K_M$ *and* $\Delta_{sM} = \frac{1}{s^2}.\Delta_M$ *, we get :*

$$(\alpha_{sM}.I + \Delta_{sM}) D_{sM} = K_{sM} \leftrightarrow \left(s.\alpha_{sm}.I + \frac{1}{s}.\Delta_m\right) D_{sM} = K_M$$

let set: $\alpha_{sM} = \frac{1}{s^2}.\alpha_M$ (1), $\leftrightarrow \left(\frac{1}{s}.\alpha_M.I + \frac{1}{s}.\Delta_M\right) D_{sM} = K_M$

let set: $D_{sM} = s.D_M$ (2) , $\leftrightarrow (\alpha_M.I + \Delta_M) D_M = K_M$

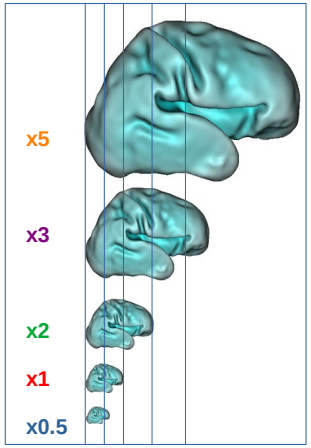
We conclude that (1) *and* (2) *are the two conditions to ensure the normalization of the DPF.*

- ► one coefficient for controlling the scale of interest
- ► one coefficient for switching between absolut and relativ dept

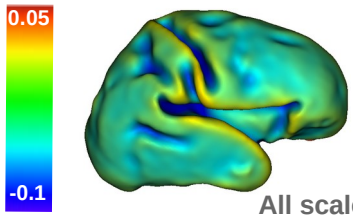
3. deal with size variations : contribution : size-controlled DPF : result

Results

A. Isometric scaling

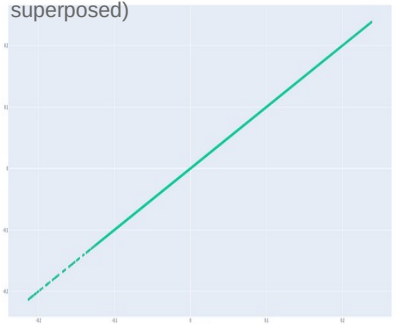


B. DPF*



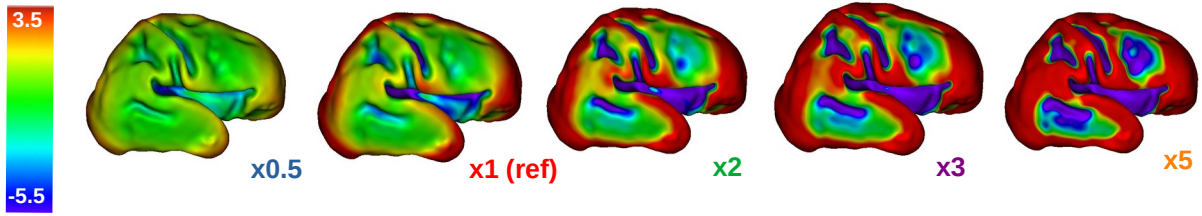
All scales (same result)

y-axis :
DPF* of scaled mesh (all superposed)

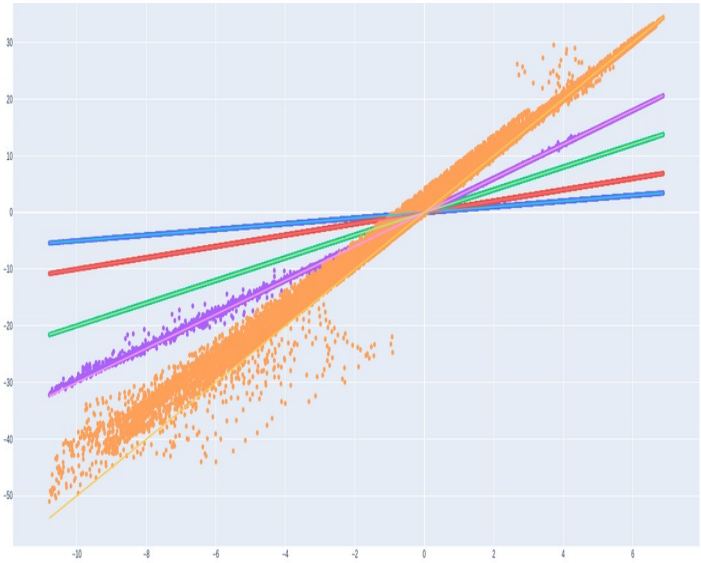


x-axis : DPF* of the ref

C. sulc from dHCP/freesurfer



yaxis :
sulc of different scaled versions of the same mesh

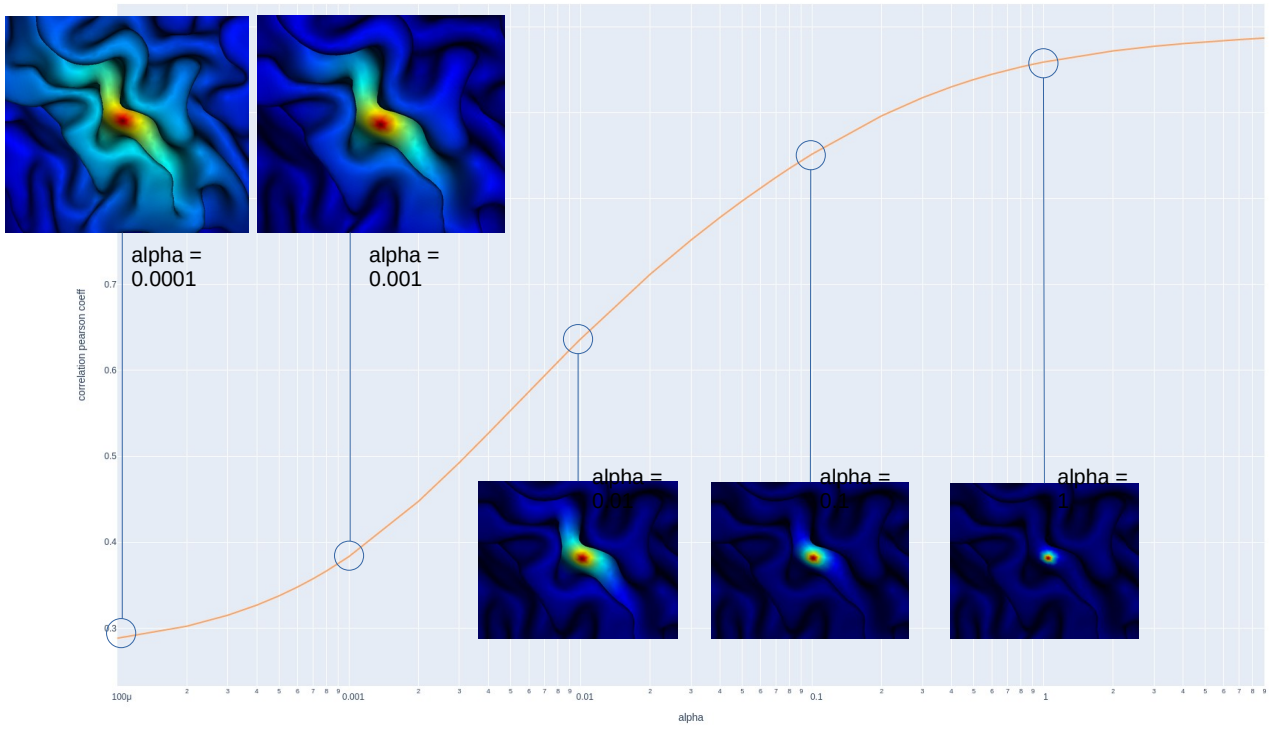


ref vs :
x5
x3
x2
x1 (ref)
x0.5

x-axis :
sulc of the ref

3. deal with size variations : contribution : size-controlled DPF

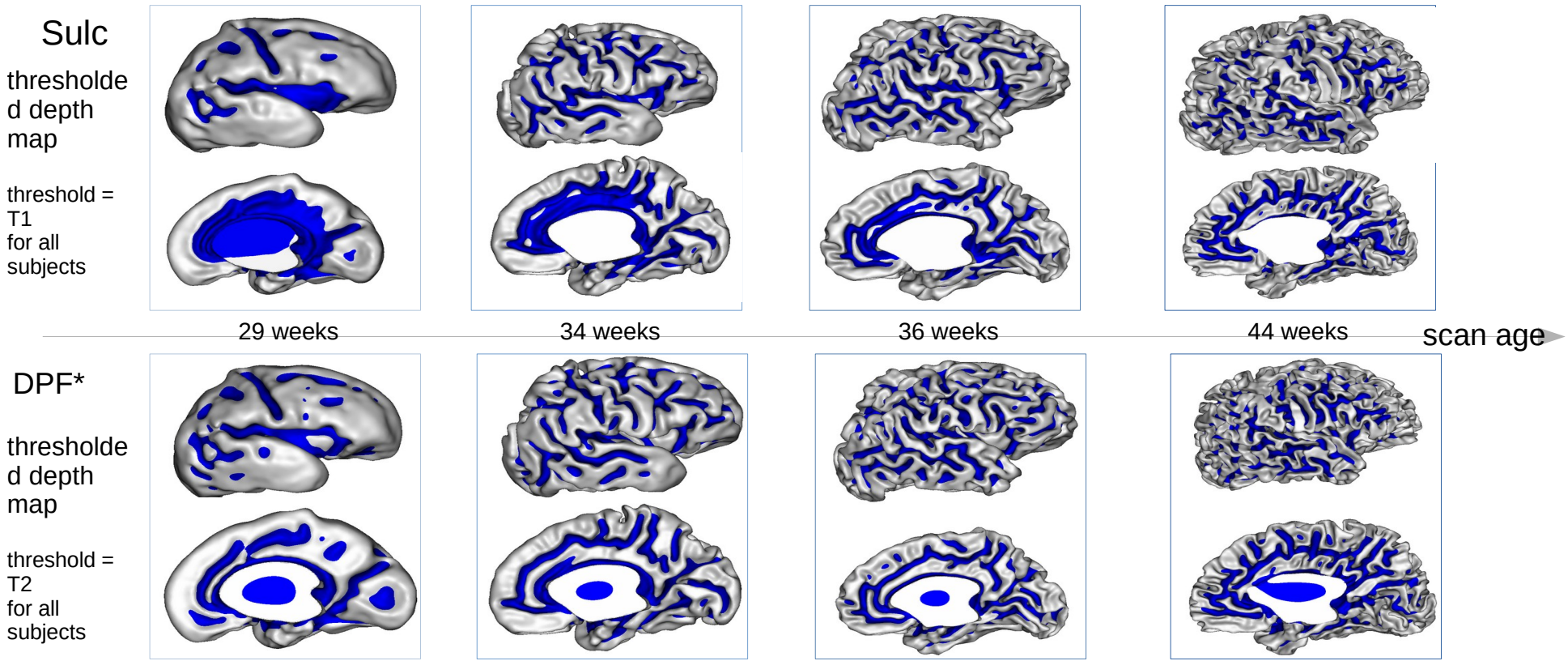
normalisation of the scale parameter : adapt the scale of interest



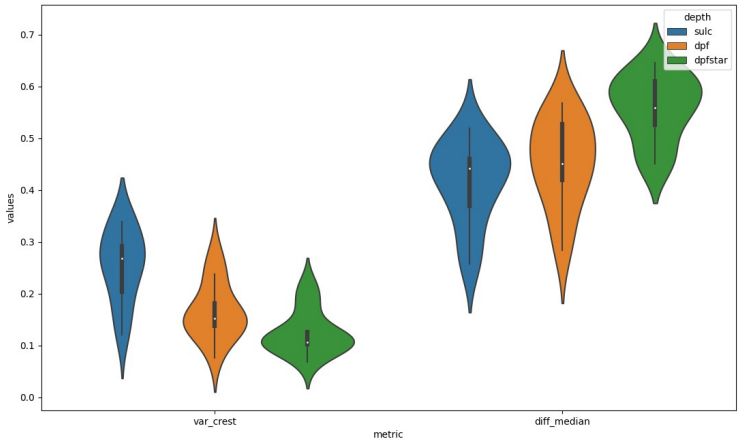
3. deal with size variations : contribution : size-controlled DPF

normalisation of the depth : switch between relativ and absolut depth

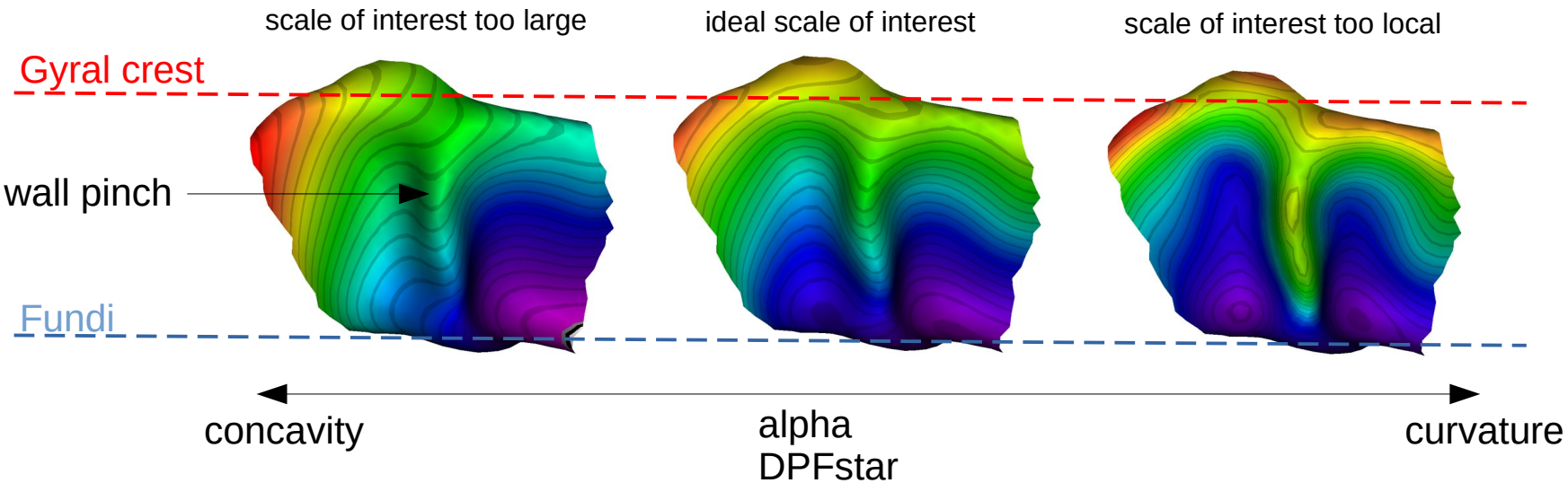
it exists on unique threshold for detect sulcal bassin whatever the size



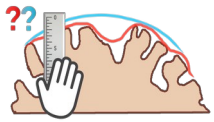
3. deal with size variations : contribution : size-controlled DPF



size controlled dpf gives better results than standard dpf !

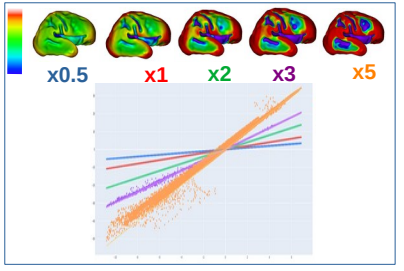


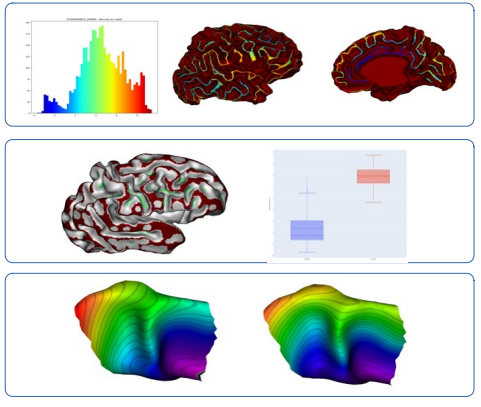
Conclusion

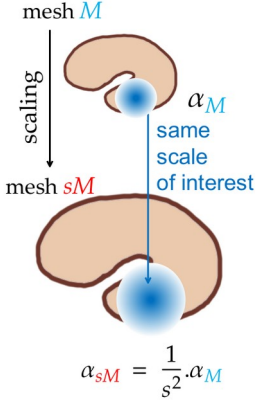


● Although the intuition behind sulcal depth is simple, it's still an **open question** to define a precise way to calculate it.
● Despite the lack of definition, there are several methods for calculating sulcal depth and it appears that sulcal depth is a promising and **relevant morphological feature** for both methodological and clinical applications.

● Distance-based methods require several pre- and post-processing steps that reduce their reliability.
● The widely used sulc method of Freesurfer shows severe spatial incoherences, especially in young brains.
● None of the methods used are easily adaptable to brain size, bringing researchers to use different methods for different sizes.
● Due to the lack of definition, there are no metrics to evaluate sulcal depth methods and this is done so far by evaluating them in terms of clinical applications.



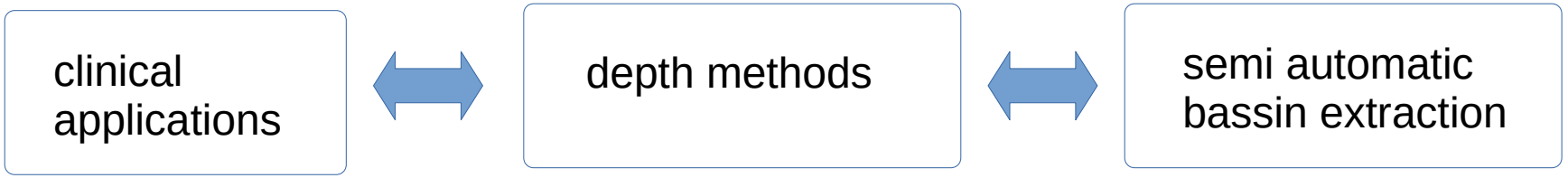




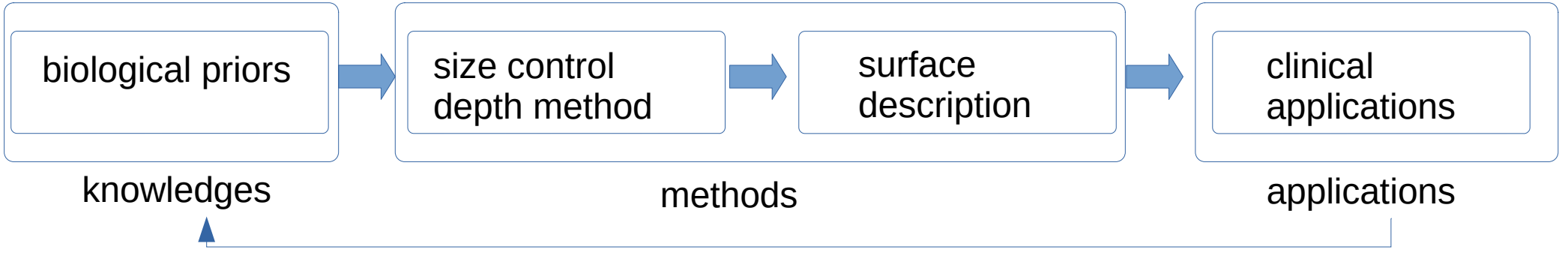
● To address these limitations in depth estimation, we propose to formally adapt **the depth potential function** with **a scale parameter** explicitly expressed as a **function of brain size**.
● And we introduce **a clear and unique framework** that expresses **properties for depth** derived from biological priors and allows quantitativ evaluation without group analysis and relativ comparaisons.
.
● Our methods gives **better results** than SULC.

Discussion

before : not a good practice for open science



After: a better practice for open science



- equation can be upgraded regarding your biological priors
- allow community to improve the methods when knowledges improve
- allow to build method on the same basement

Perspectives

Theory : A very flexible equation

- improve the isometric scaling with an allometric scaling
- add constraint terms

Practice : analyse spatial distribution and temporal emergence for early malformation detections

- improve reliability of sulcal pits extraction algorithm (Auzias et al, 2015)
- use sulcal pit extraction method to improve the Multimodal Surface Matching algorithm (Robinson et al. 2014)
- to generate cortical surface templates at each week of gestation between 20 and 40 weeks.

These new tools will allow me to assess the spatial distribution and temporal emergence of sulcal roots to characterise folding dynamics in healthy and malformed fetuses.

use the fetal MRI database acquired at the Timone Hospital as part of routine clinical practice, built in parallel with my thesis :

- 560 MRI scans of fetuses with no abnormalities,
- 90 fetuses with agenesis of the corpus callosum
- 20 fetuses with cerebral malformations such as microcephaly, macrocephaly or polymicrogyria.

Thanks,