Neuroimaging in Developmental Coordination Disorder: a review with a focus on comorbidity

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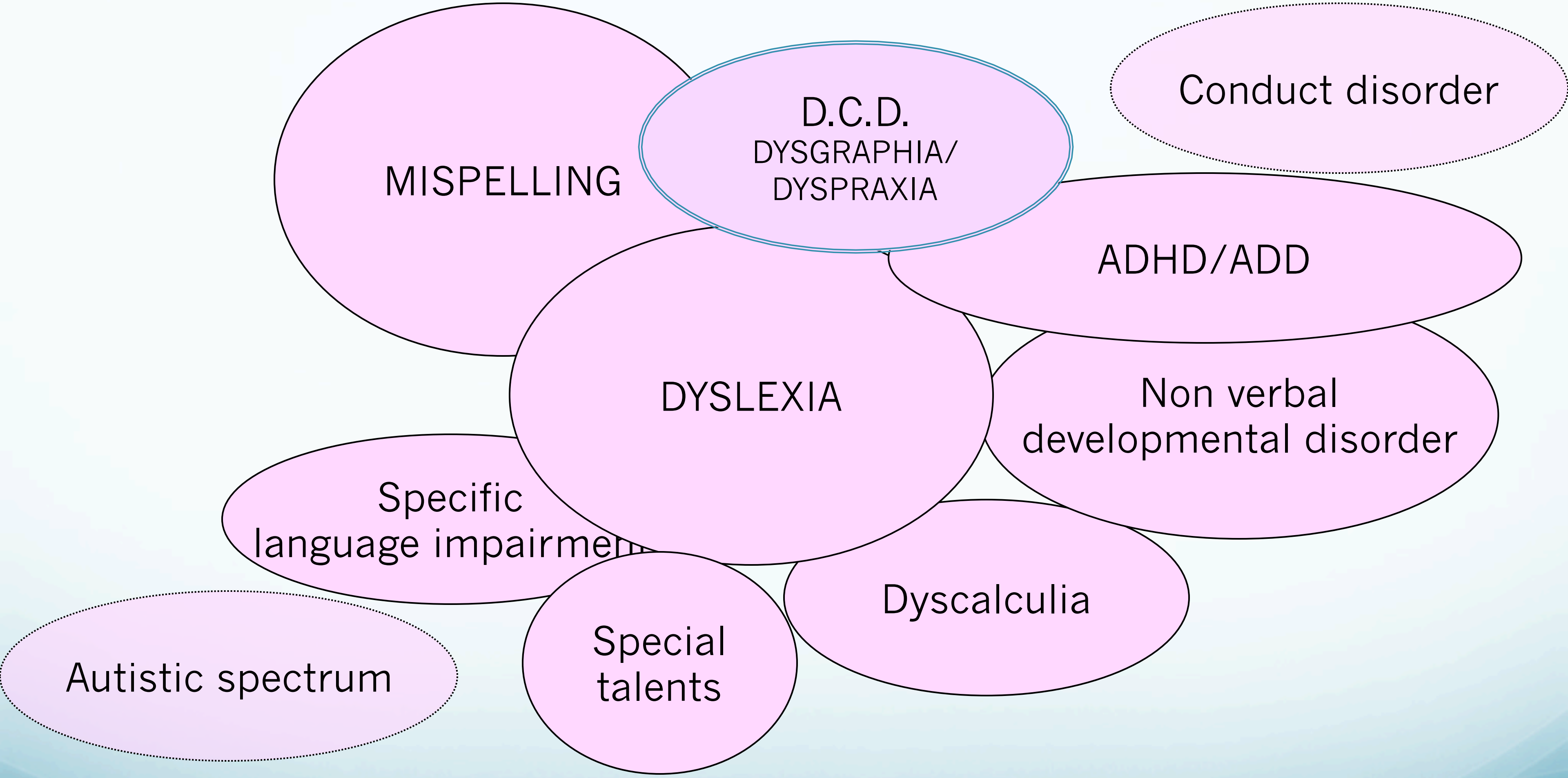
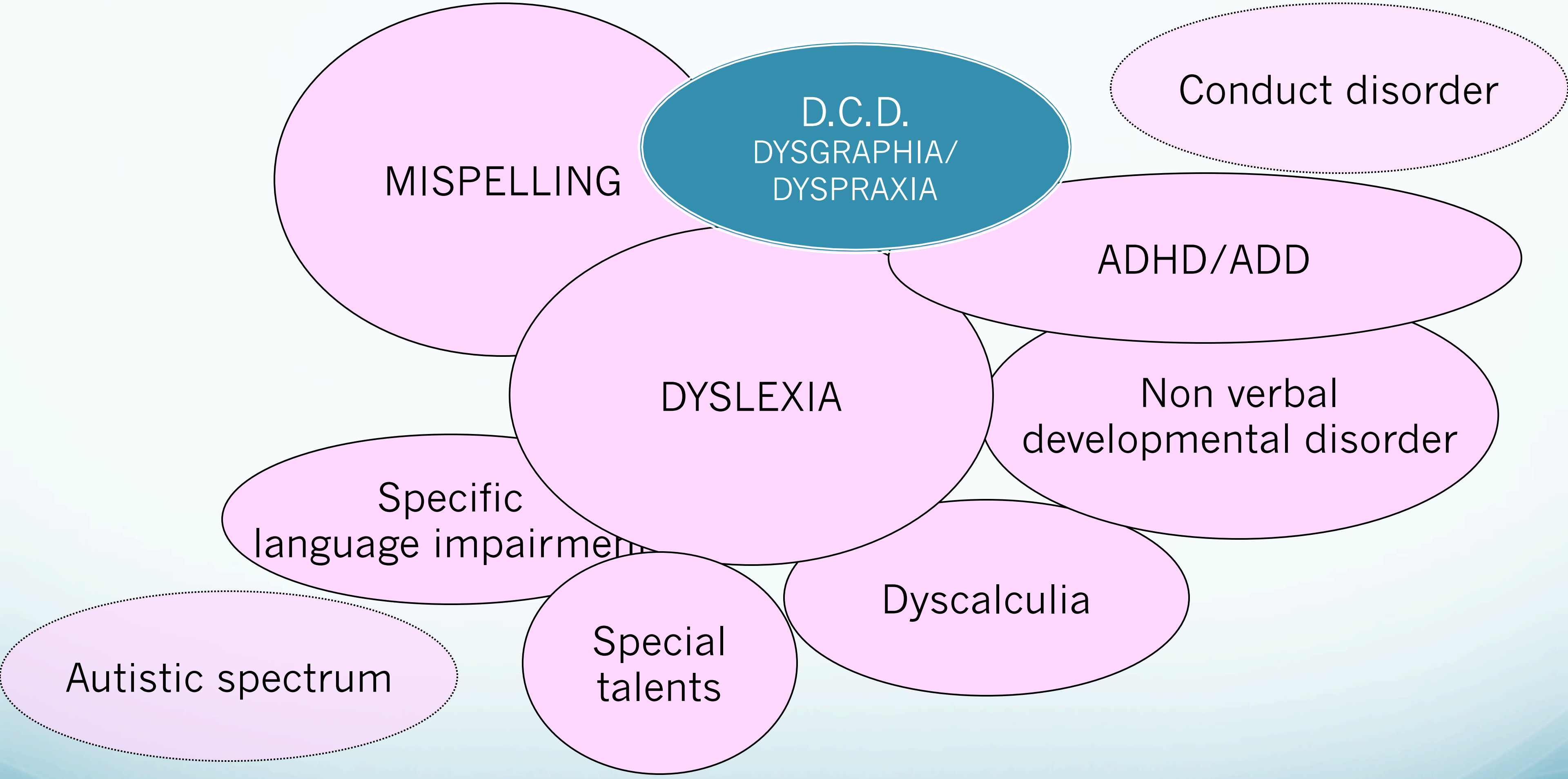
Overview of lecture

- General considerations about DCD, comorbidity and modularity (the "dysconstellation"), adult models available to date
- Summary of available imaging studies:
  - Functional imaging (bold/resting state)
  - Morphological imaging (DTI/cortical thickness)
- DCD among other neurodevelopmental disorders : similarities and differences
  - Dyslexia, dyscalculia
  - ADHD
  - Autism spectrum
  - Intellectual giftedness
- Toward an integrative model of neurodevelopmental disorders with emphasis on impaired connectivity

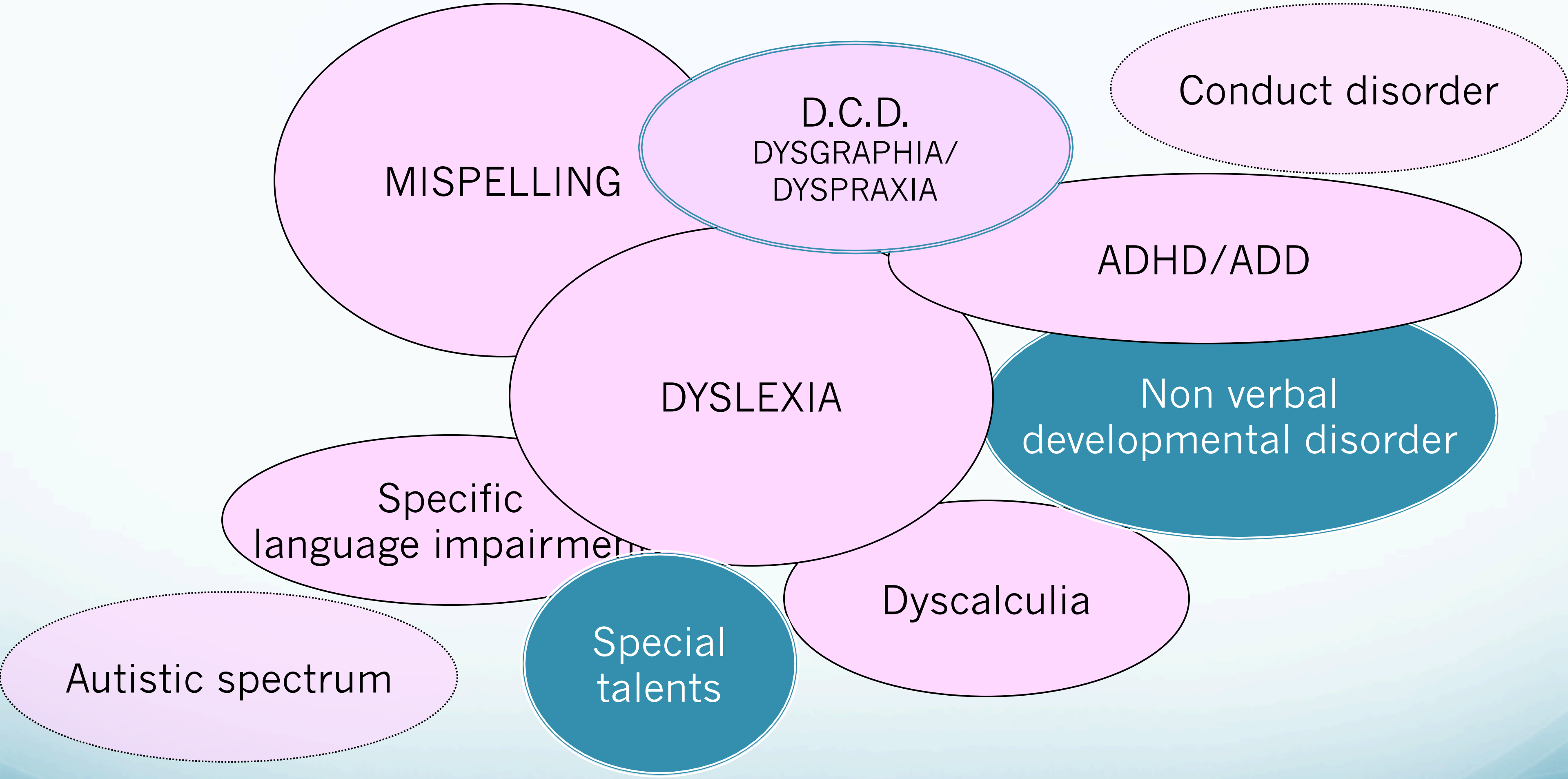
Part 1 : general considerations



The « dysconstellation » : a modulary vision of the cognitive disorders having an impact on learning



The « dysconstellation » : a modulary vision of the cognitive disorders having an impact on learning



MISPELLING

D.C.D.
DYSGRAPHIA/
DYSPRAXIA

Conduct disorder

ADHD/ADD

DYSLEXIA

Non verbal
developmental disorder

Specific
language impairmen

Dyscalculia

Autistic spectrum

Special
talents

The « dysconstellation » : a modulary vision of the cognitive disorders having an impact on learning

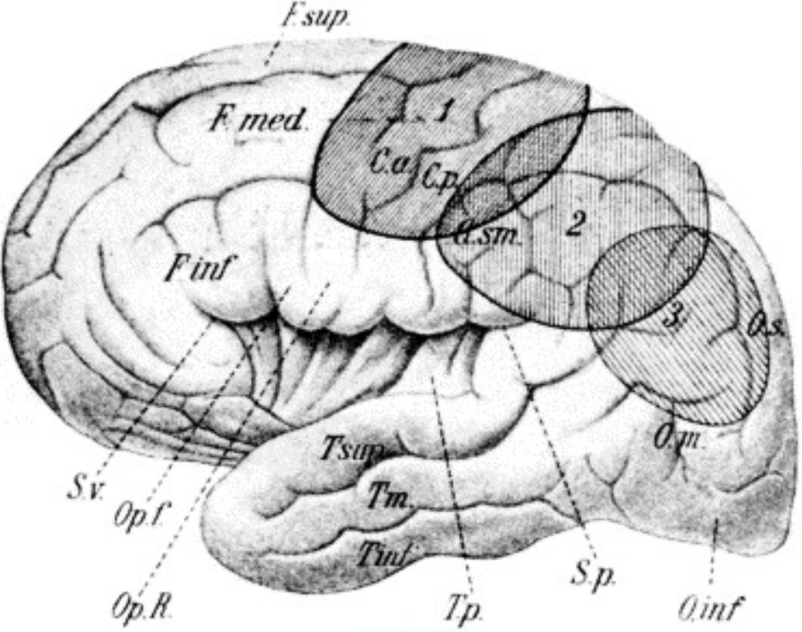
Attention deficit disorder (hyperactivity)

Developmental coordination disorder

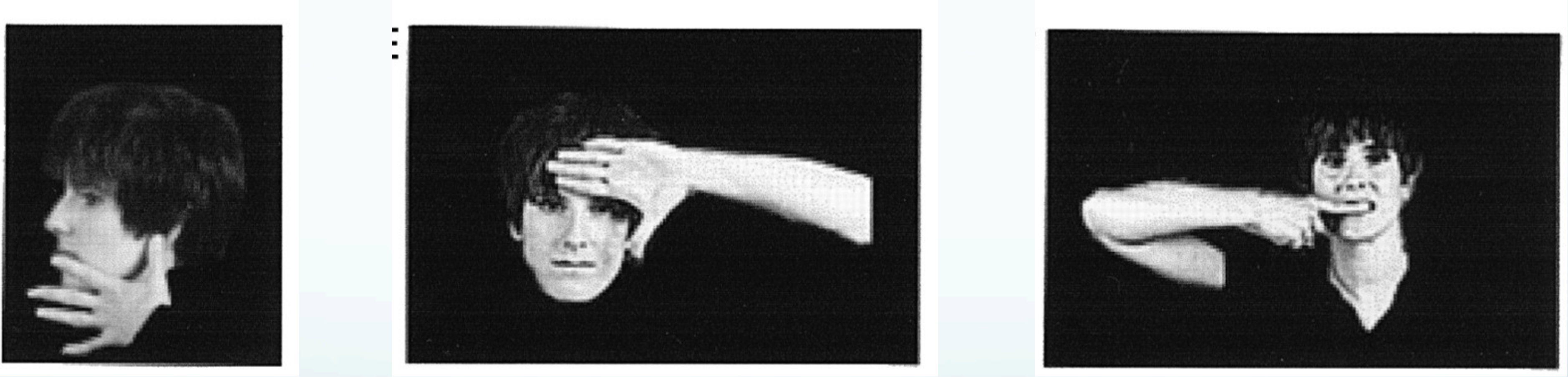
Nonverbal learning disability

High potential (intellectually gifted)

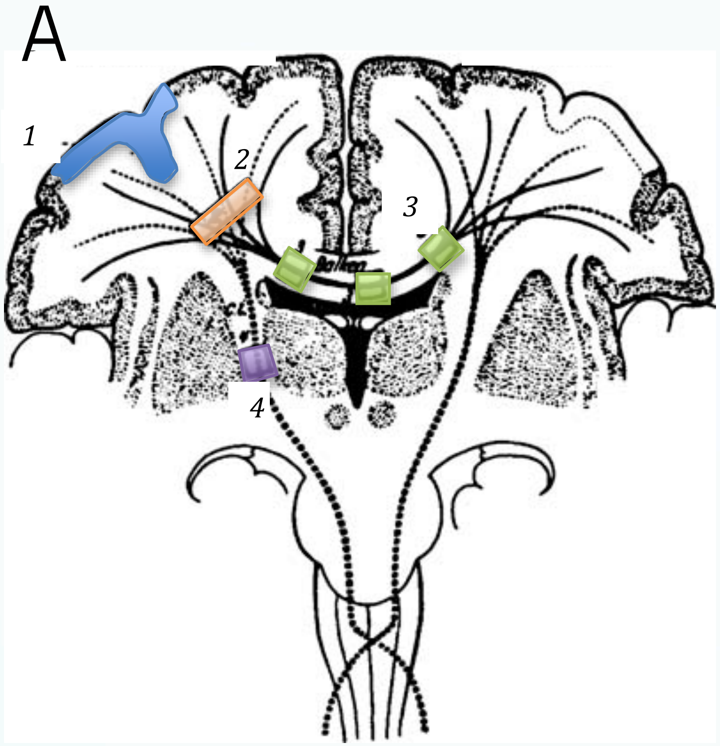
Asperger (autism spectrum)



Classical representaiton from the early XXth century of the brain substrate of the main 3 forms of limb apraxia : ideational (3) , ideo-motor (2) and melokinetic or limb-kinetic (1) according to Liepmann’s conception.

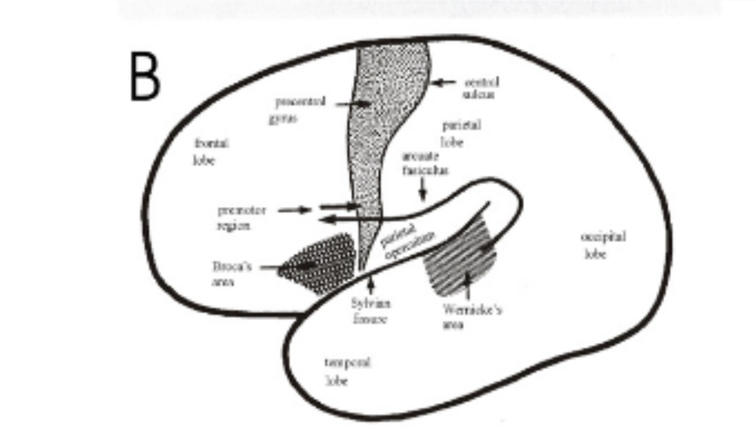


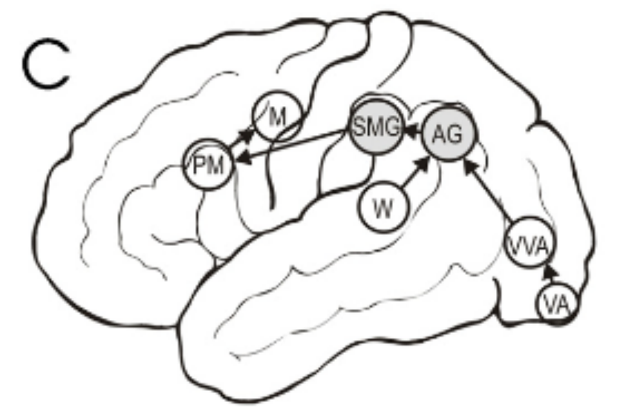
Ideomotor apraxia : imitation of non-sense gesture, execution on command of intransitive (military salute) of transitive (teeth brushing) gestures



A/ Liepmann's original drawing explaining the occurrence of left-hand apraxia fronm various lesions : left parietal, left subcortical, or callosal.

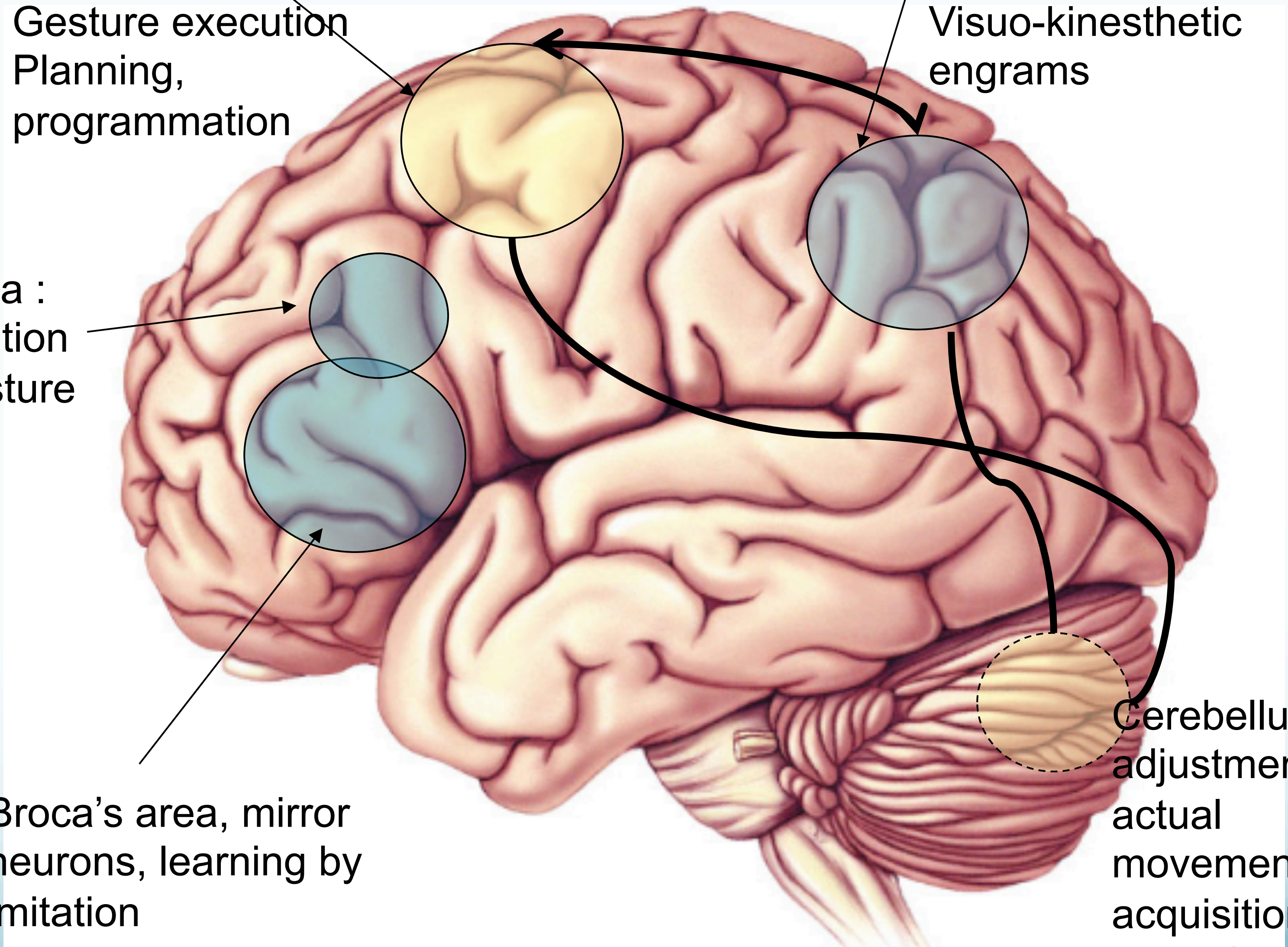
B/ Geschwind concept of disconnection syndrome between Wernicke's area (comprehension of gestures) and premotor cortex (motor exécution)





C/ Heilman model considering apraxia as the consequence of destruction of motor engrams in the inferior parietal lobe rather than disconnection.

Summary of functional imaging of voluntary movements



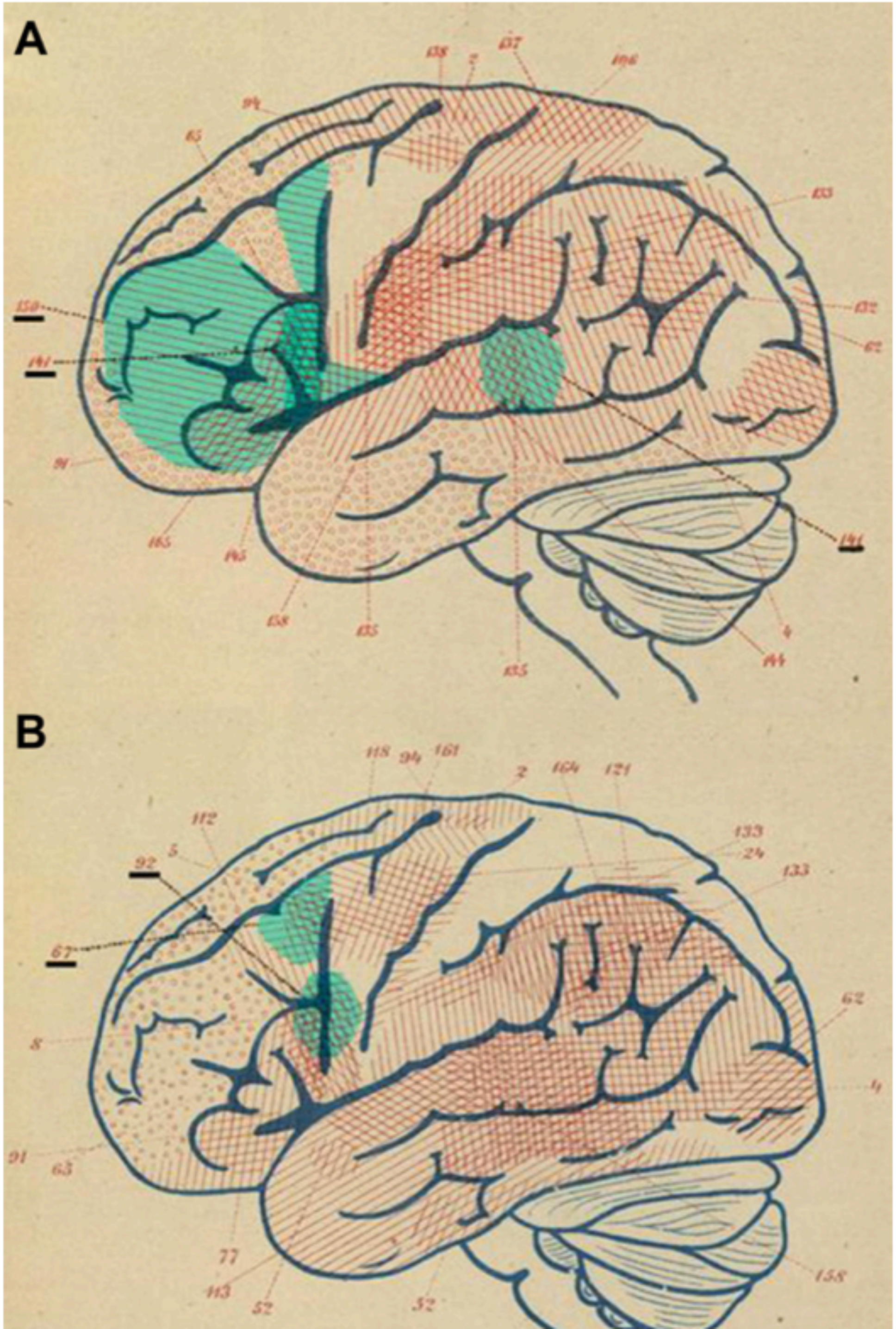
Frontal cortex (DLPFC)
Gesture execution
Planning, programmation

Parietal lobe : preparing gestures. Visuo-kinesthetic engrams

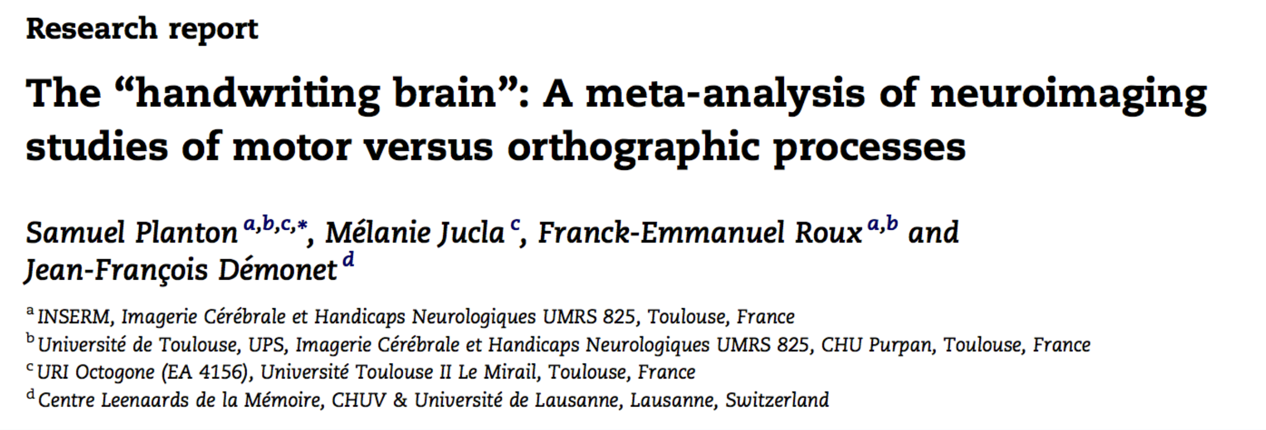
Exner’s area : programmation graphic gesture

Broca’s area, mirror neurons, learning by imitation

Cerebellum : adjustment of actual movement, acquisition of procedures, movement timing



Exner (1888) : 4 cas avec agraphie, dont trois touchant le gyrus frontal moy. gauche (et 3 le gyrus frontal inf, aire de Broca)



Research report

The "handwriting brain": A meta-analysis of neuroimaging studies of motor versus orthographic processes

Samuel Planton [a,b,c,], Mélanie Jucla [c], Franck-Emmanuel Roux [a,b] and Jean-François Démonet [d]*

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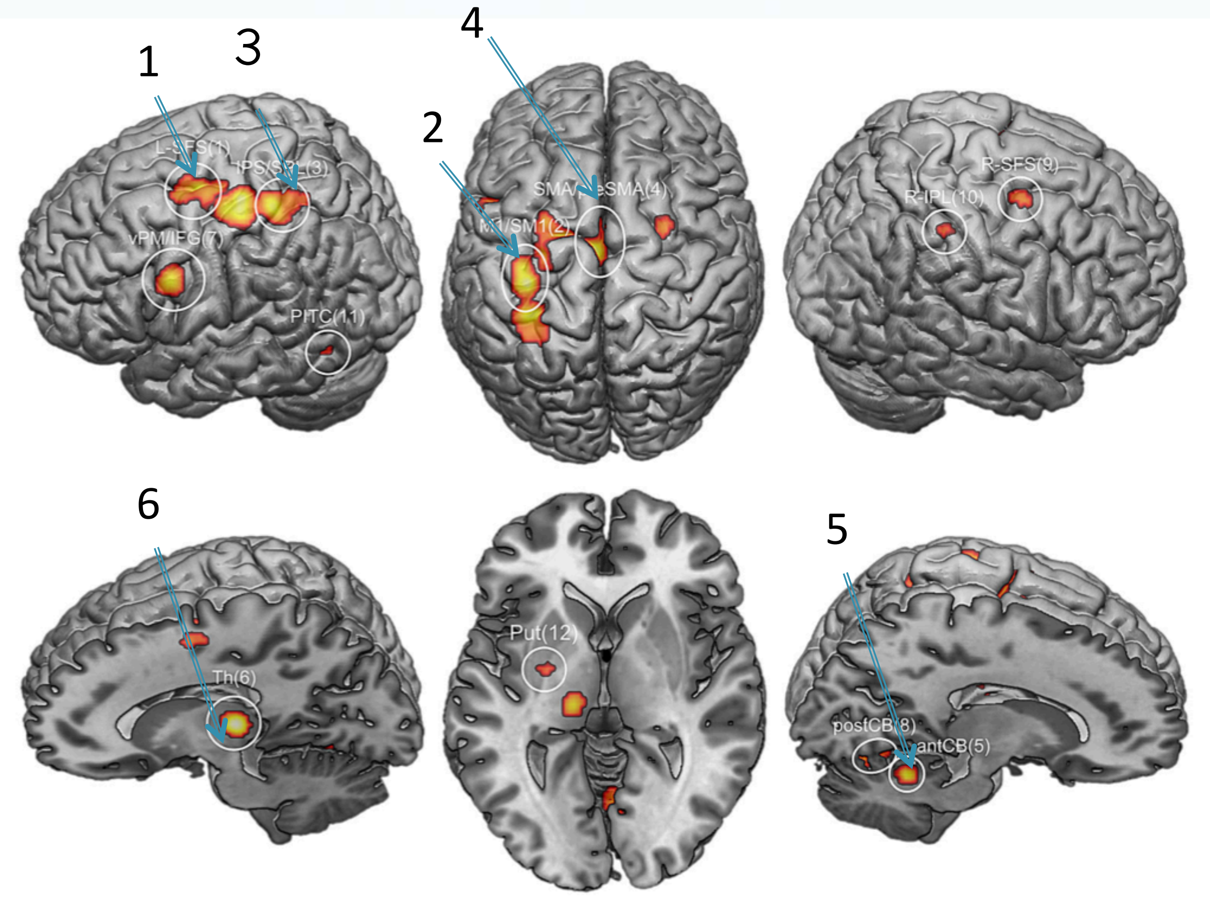


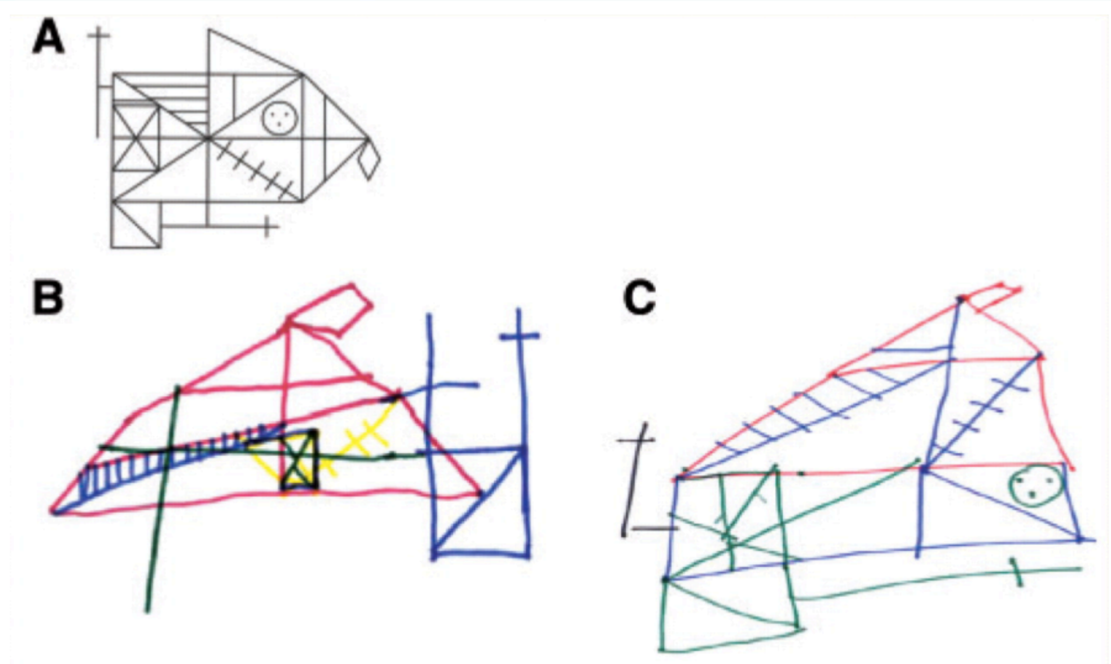
Meta-analysis of 18 studies for a total of 229 individuals and 462 foci of activation.

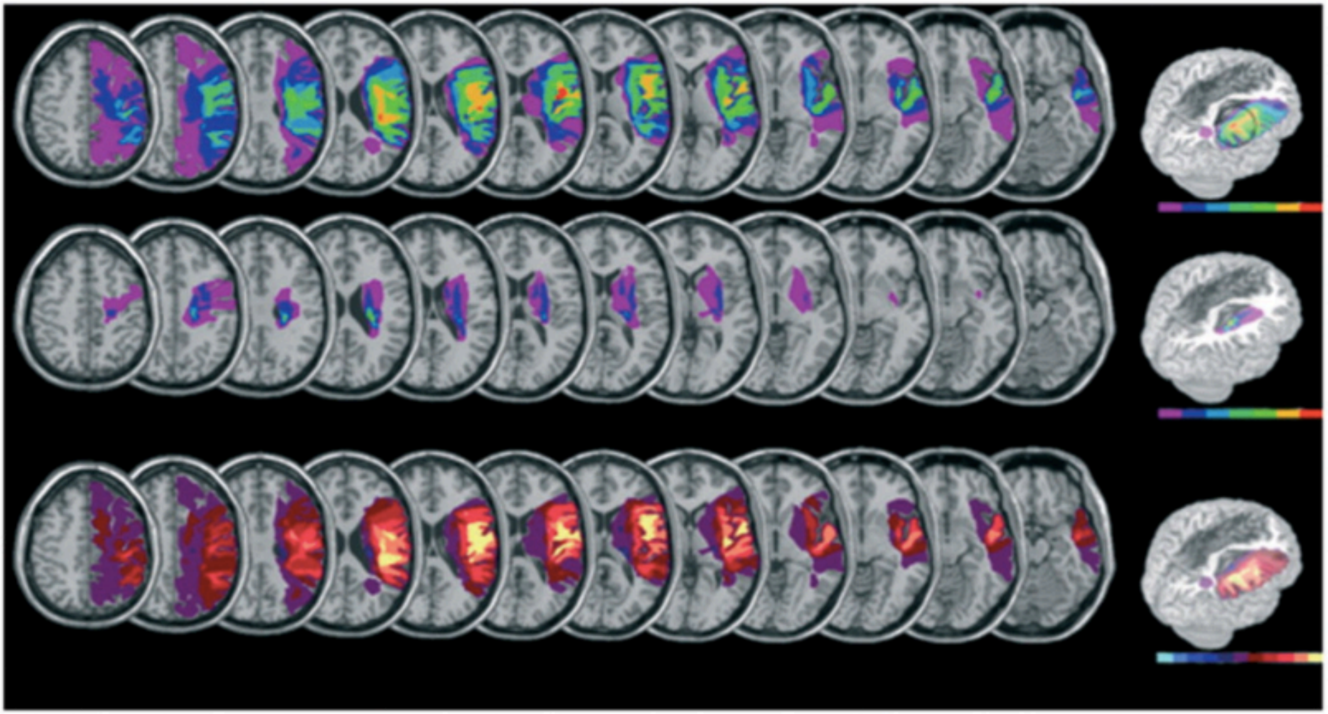
Zones described as active during handwriting : in decreasing order of frequency:

1. Left superior frontal sulcus
2. Primary sensory-motor cortex
3. Left superior parietal area
4. : SMA and pre-SMA
5. Anterior cerebellum
6. Thalamus…

The special case of constructional apraxia

Right-hemisphere constructional apraxia : lack of accurate spatial relations between components of objects and an incoherent, disjointed quality. However, damage to the left hemisphere produces qualitatively different drawing performance with an oversimplification of figures and a perseveration on items suggestive of planning deficits





Cases without C.A.

Cases with C.A.

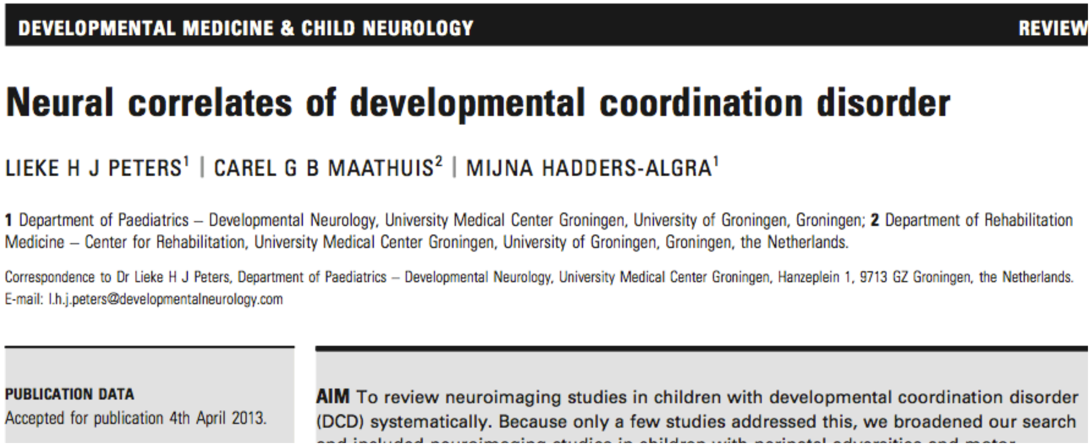
Summary (part 1)

- It is thus obvious, from this quick overview of the literature, that classical data obtained in lesion or functional imaging studies do not provide any convincing model on which observations on DCD children could be easily matched.

- For example the strong left-hemisphere lateralisation of the control of voluntary movements, as well as the strong right-hemisphere lateralisation of visuo-constructional processes, which are the hallmarks of the two main forms of apraxia in adults, do not have equivalence in developmental pathology.

- Overall, there is still unresolved ambiguity between the separability of gestural and spatial cognition in adult models and the most often entangled levels of motor, spatial, and temporal involvement in developmental coordination disorder.

Part 2 : brain imaging in DCD



DEVELOPMENTAL MEDICINE & CHILD NEUROLOGY **REVIEW**

Neural correlates of developmental coordination disorder

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AIM To review neuroimaging studies in children with developmental coordination disorder (DCD) systematically. Because only a few studies addressed this, we broadened our search

- The studies consisted of four functional MRI (fMRI) studies and one diffusion tensor imaging study.
- The number of participants in study groups and comparison groups varied from seven to 12
- Alterations in multiple brain areas during motor and attention/inhibition tasks : frontal, temporal, and parietal lobes, and cerebellum.
- *"This suggests that the neural substrate of DCD is dysfunction in multiple areas of the brain rather than dysfunction restricted to one specific area"*

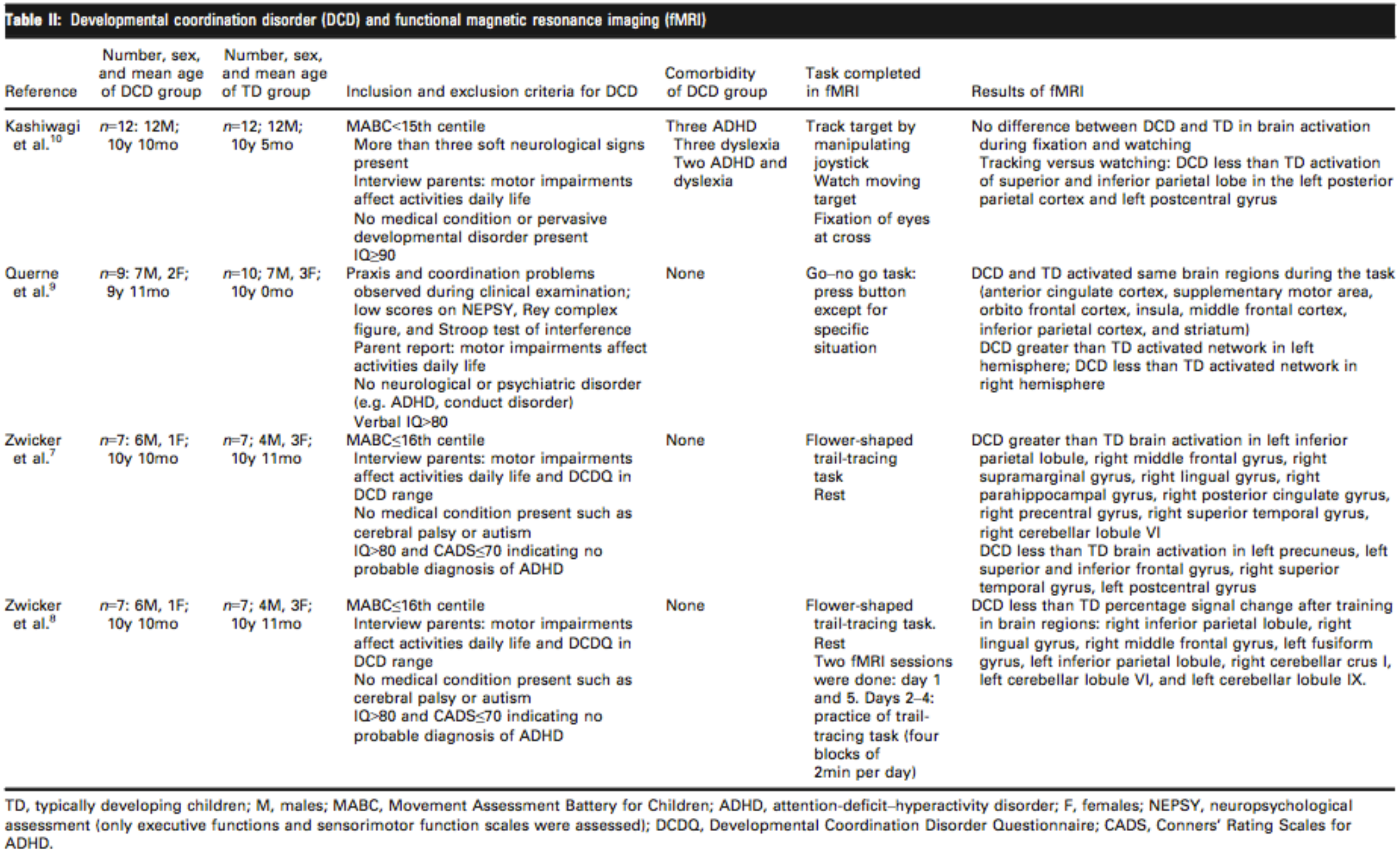
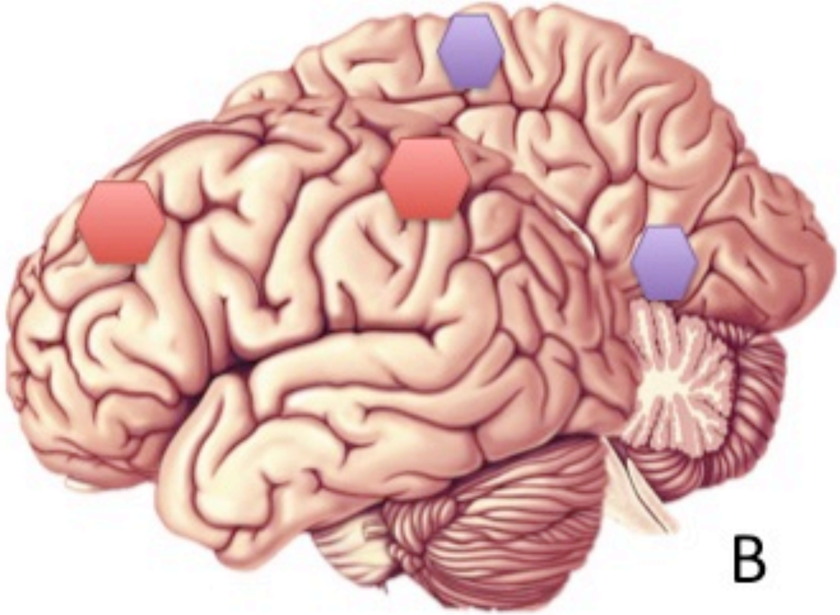
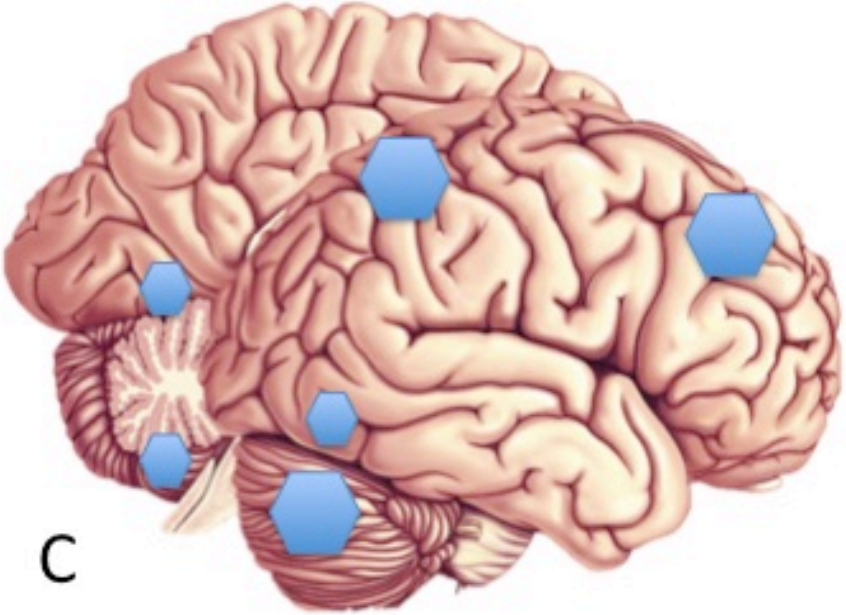


Table II: Developmental coordination disorder (DCD) and functional magnetic resonance imaging (fMRI)

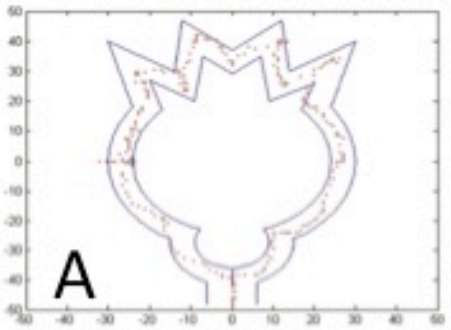
Reference	Number, sex, and mean age of DCD group	Number, sex, and mean age of TD group	Inclusion and exclusion criteria for DCD	Comorbidity of DCD group	Task completed in fMRI	Results of fMRI
Kashiwagi et al.[10]	*n*=12: 12M; 10y 10mo	*n*=12; 12M; 10y 5mo	MABC<15th centile More than three soft neurological signs present Interview parents: motor impairments affect activities daily life No medical condition or pervasive developmental disorder present IQ≥90	Three ADHD Three dyslexia Two ADHD and dyslexia	Track target by manipulating joystick Watch moving target Fixation of eyes at cross	No difference between DCD and TD in brain activation during fixation and watching Tracking versus watching: DCD less than TD activation of superior and inferior parietal lobe in the left posterior parietal cortex and left postcentral gyrus
Querne et al.[9]	*n*=9: 7M, 2F; 9y 11mo	*n*=10; 7M, 3F; 10y 0mo	Praxis and coordination problems observed during clinical examination; low scores on NEPSY, Rey complex figure, and Stroop test of interference Parent report: motor impairments affect activities daily life No neurological or psychiatric disorder (e.g. ADHD, conduct disorder) Verbal IQ>80	None	Go–no go task: press button except for specific situation	DCD and TD activated same brain regions during the task (anterior cingulate cortex, supplementary motor area, orbito frontal cortex, insula, middle frontal cortex, inferior parietal cortex, and striatum) DCD greater than TD activated network in left hemisphere; DCD less than TD activated network in right hemisphere
Zwicker et al.[7]	*n*=7: 6M, 1F; 10y 10mo	*n*=7; 4M, 3F; 10y 11mo	MABC≤16th centile Interview parents: motor impairments affect activities daily life and DCDQ in DCD range No medical condition present such as cerebral palsy or autism IQ>80 and CADS≤70 indicating no probable diagnosis of ADHD	None	Flower-shaped trail-tracing task Rest	DCD greater than TD brain activation in left inferior parietal lobule, right middle frontal gyrus, right supramarginal gyrus, right lingual gyrus, right parahippocampal gyrus, right posterior cingulate gyrus, right precentral gyrus, right superior temporal gyrus, right cerebellar lobule VI DCD less than TD brain activation in left precuneus, left superior and inferior frontal gyrus, right superior temporal gyrus, left postcentral gyrus
Zwicker et al.[8]	*n*=7: 6M, 1F; 10y 10mo	*n*=7; 4M, 3F; 10y 11mo	MABC≤16th centile Interview parents: motor impairments affect activities daily life and DCDQ in DCD range No medical condition present such as cerebral palsy or autism IQ>80 and CADS≤70 indicating no probable diagnosis of ADHD	None	Flower-shaped trail-tracing task. Rest Two fMRI sessions were done: day 1 and 5. Days 2–4: practice of trail-tracing task (four blocks of 2min per day)	DCD less than TD percentage signal change after training in brain regions: right inferior parietal lobule, right lingual gyrus, right middle frontal gyrus, left fusiform gyrus, left inferior parietal lobule, right cerebellar crus I, left cerebellar lobule VI, and left cerebellar lobule IX.

TD, typically developing children; M, males; MABC, Movement Assessment Battery for Children; ADHD, attention-deficit–hyperactivity disorder; F, females; NEPSY, neuropsychological assessment (only executive functions and sensorimotor function scales were assessed); DCDQ, Developmental Coordination Disorder Questionnaire; CADS, Conners' Rating Scales for ADHD.



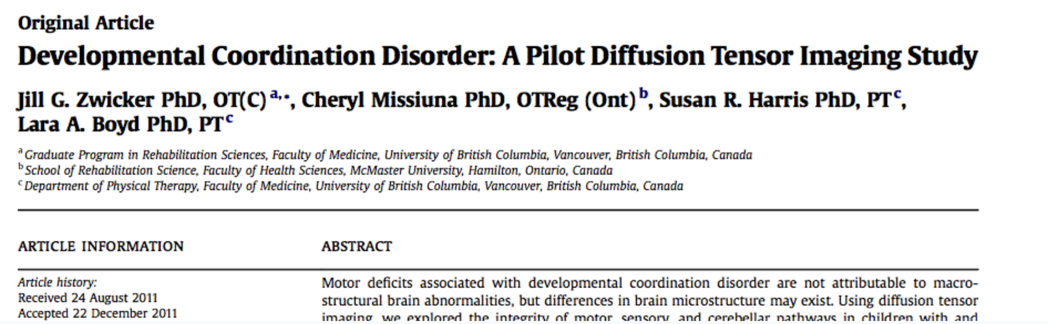


Brain activity recording
during the motor act of
tracing itself : DCD>CONT



Measure of effect of
learning the same task
(Before/after learning)):
DCD<CONT

DCD children overactivate a mainly left hemisphere network when achieving the task and underactivate a mainly right hemisphere network, in addition to bilateral temporal and cerebellum, when one compare before and after training. (Zwicker et al.)



Original Article

Developmental Coordination Disorder: A Pilot Diffusion Tensor Imaging Study

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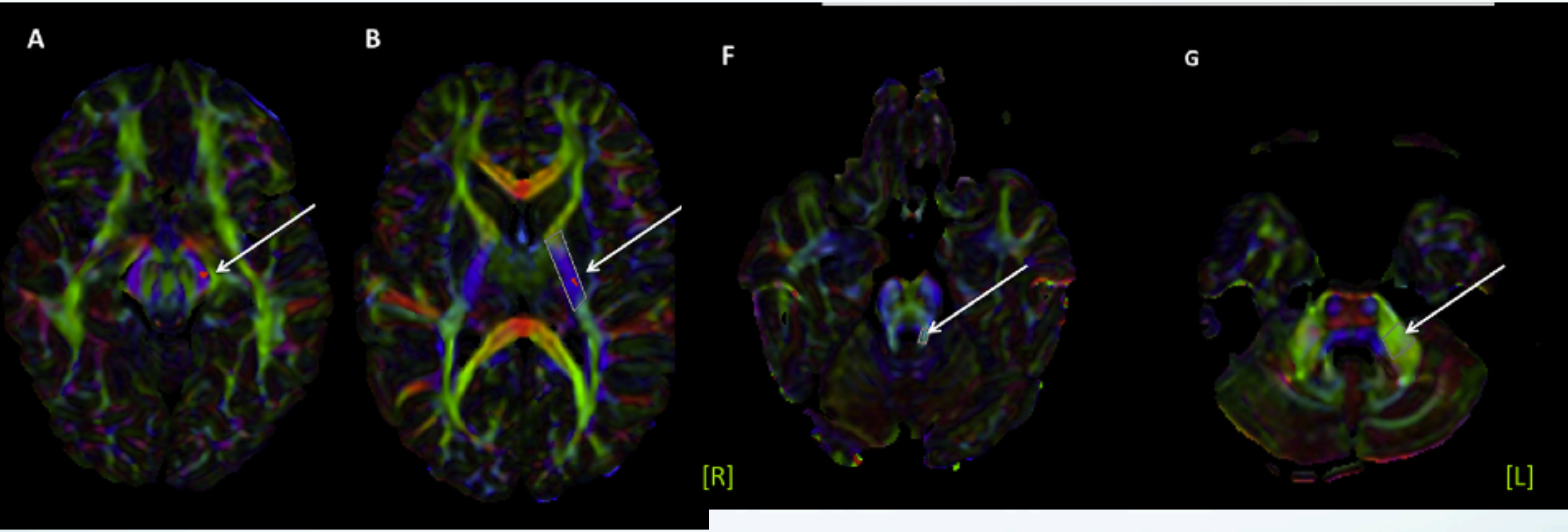
ABSTRACT

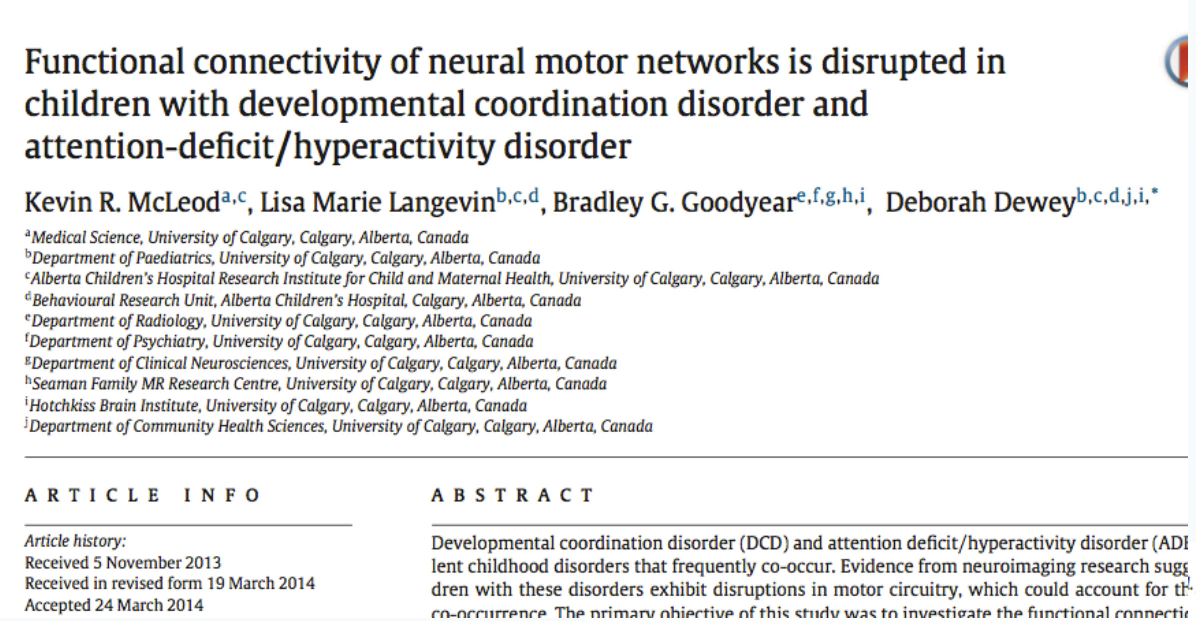
Motor deficits associated with developmental coordination disorder are not attributable to macro-structural brain abnormalities, but differences in brain microstructure may exist. Using diffusion tensor imaging, we explored the integrity of motor, sensory, and cerebellar pathways in children with and



Decreased mean diffusivity (but not fractional anisotropy) of the corticospinal tract and posterior thalamic radiation in DCD

Significantly correlated with motor impairment scores on the Movement Assessment Battery for Children-2

"we were surprised to observe no differences between children with and without developmental coordination disorder in mean diffusivity and fractional anisotropy in the superior and middle cerebellar peduncles".



Functional connectivity of neural motor networks is disrupted in children with developmental coordination disorder and attention-deficit/hyperactivity disorder

Kevin R. McLeod[a,c], Lisa Marie Langevin[b,c,d], Bradley G. Goodyear[e,f,g,h,i], Deborah Dewey[b,c,d,j,i,*]

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A R T I C L E I N F O

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A B S T R A C T

Developmental coordination disorder (DCD) and attention deficit/hyperactivity disorder (AD
lent childhood disorders that frequently co-occur. Evidence from neuroimaging research sugg
dren with these disorders exhibit disruptions in motor circuitry, which could account for th
co-occurrence. The primary objective of this study was to investigate the functional connecti

/ NeuroImage: Clinical 4 (2014) 566–575

- Resting-state fMRI was performed on seven children with DCD, 21 with ADHD, 18 with DCD + ADHD and 23 controls.
- Relative to controls, children with DCD and/or ADHD exhibited similar **reductions in functional connectivity** between the primary motor cortex and the bilateral inferior frontal gyri, right supramarginal gyrus, angular gyri, insular cortices, amygdala, putamen, and pallidum.

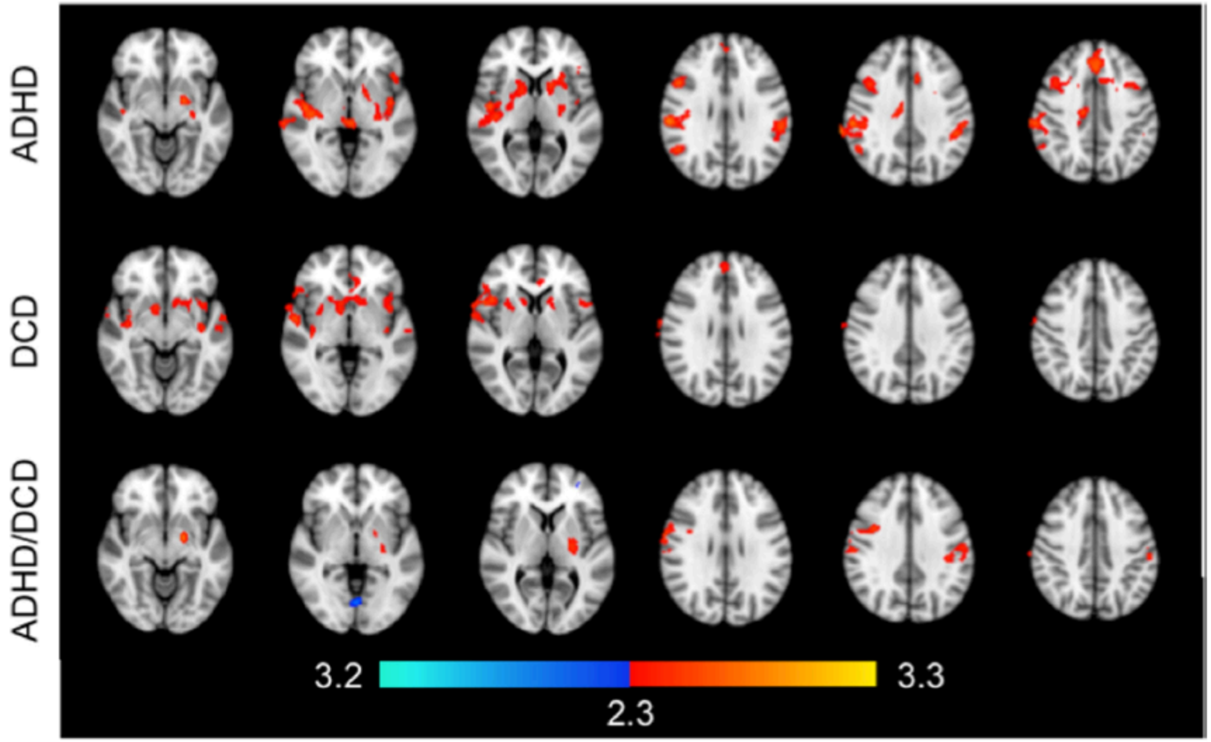

Fig. 1. Regions exhibiting greater (red) and lower (blue) functional connectivity with left M1 in controls compared to children in the ADHD (top), DCD (middle), and DCD + AD
(bottom) groups. Colors indicate statistical significance, expressed as *Z*-scores.

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ORIGINAL ARTICLES

Common White Matter Microstructure Alterations in Pediatric Motor and Attention Disorders

Lisa Marie Langevin, PhD[1,2,3,4], Frank P. MacMaster, PhD[1,2,3,4,5,6], Susan Crawford, MSc[1,3,4], Catherine Lebel, PhD[2,3,7], and Deborah Dewey, PhD[1,2,3,4,8]

In 85 children with DCD, ADHD, or both, we examined with DTI, the corpus callosum, superior longitudinal fasciculus, and cingulum

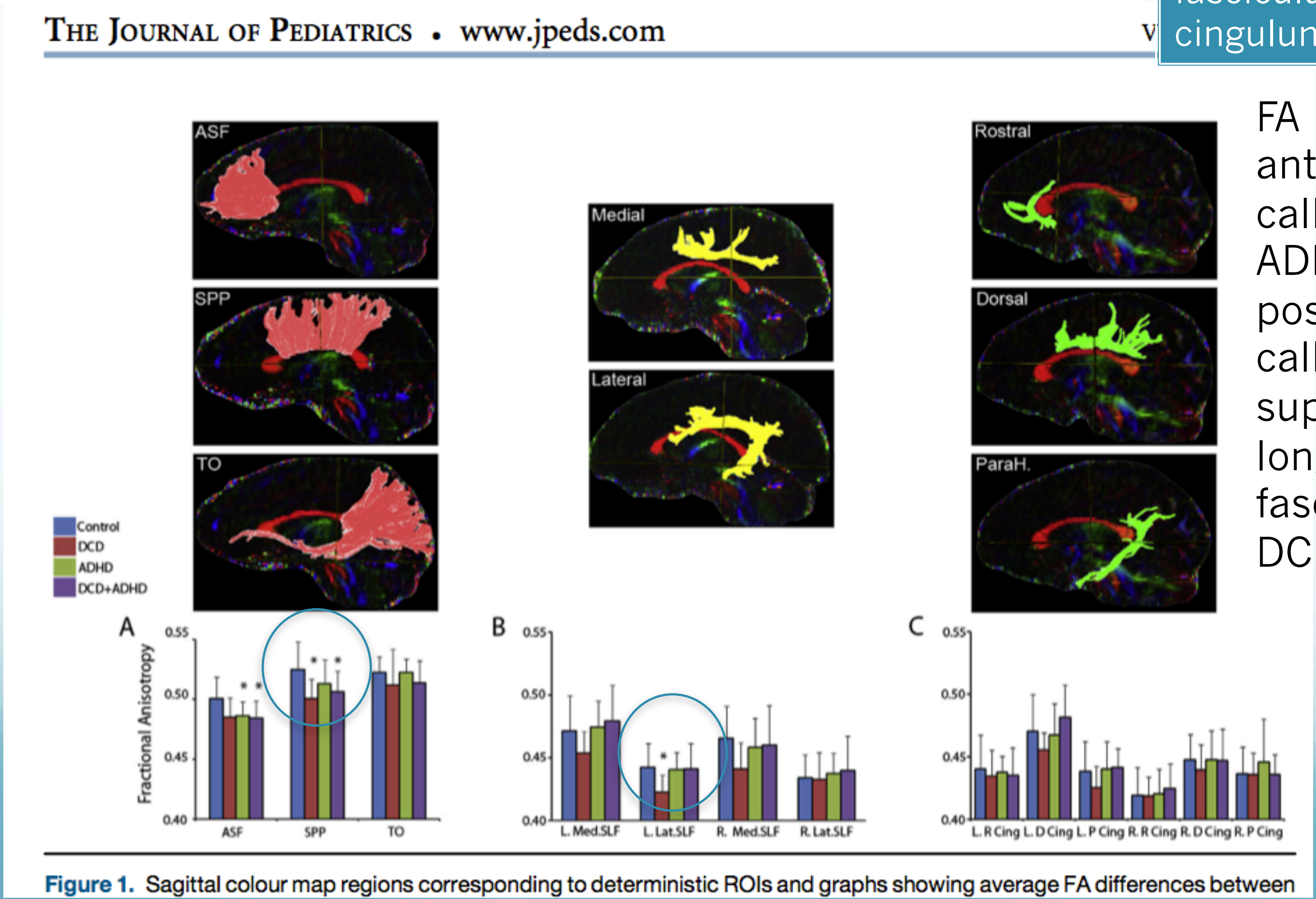

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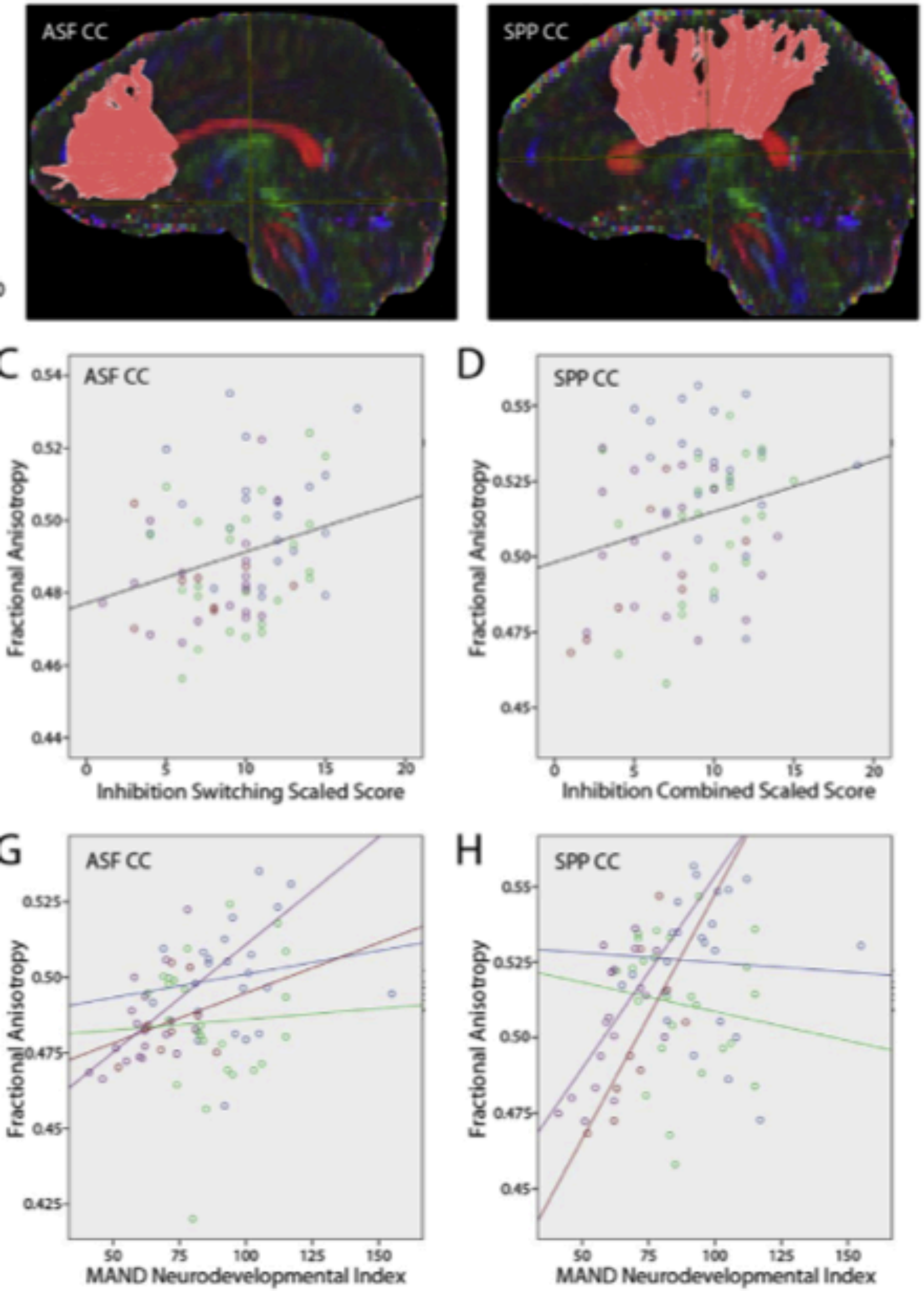
Figure 1. Sagittal colour map regions corresponding to deterministic ROIs and graphs showing average FA differences between

FA reduction in anterior callosum for ADHD and posterior callosum and superior longitudinal fasciculus for DCD



Callosal radiations : anterior superior frontal (ASF) – superior posterior parietal (SPP)

Correlations with executive function

Correlations with motor function

DEVELOPMENTAL MEDICINE & CHILD NEUROLOGY **ORIGINAL ARTICLE**

Distinct patterns of cortical thinning in concurrent motor and attention disorders

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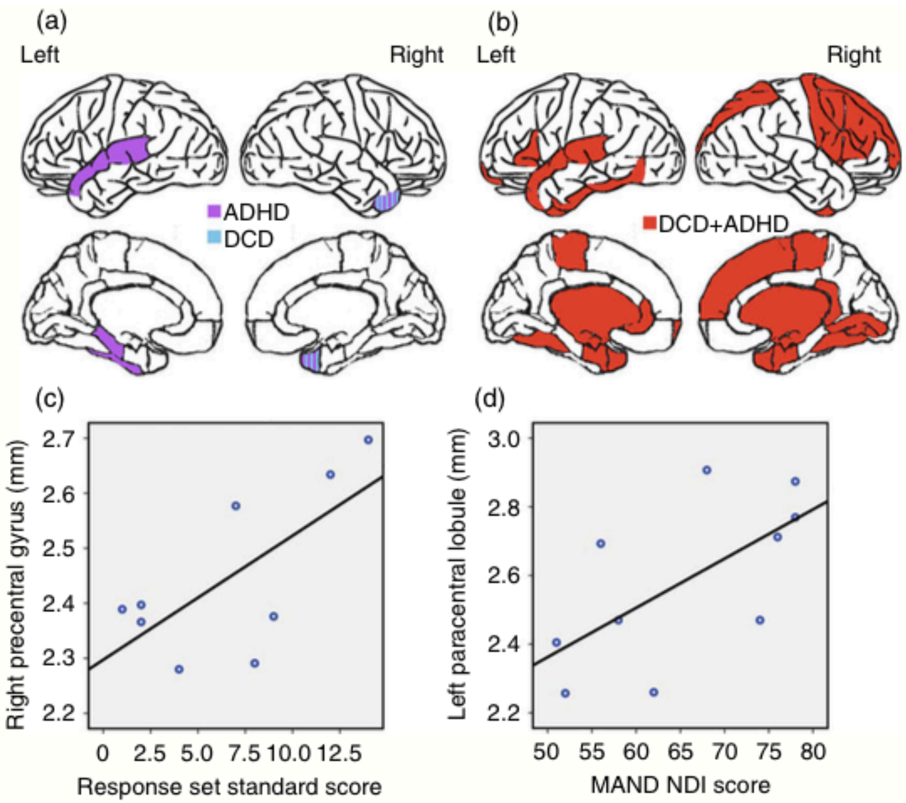
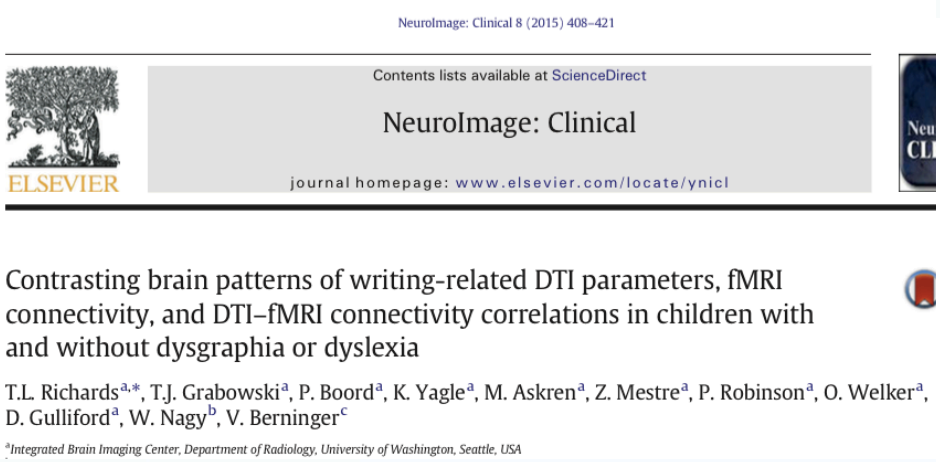
- We examined children with single and comorbid motor and attention issues for cortical thickness differences.
- In participants with ADHD alone, thickness reductions were found in the left superior temporal gyrus and parahippocampal gyrus.
- In participants with DCD alone, cortical thickness reductions were found in the medial orbitofrontal cortex.
- In comorbid DCD+ADHD, global cortical thinning deficits were found in the frontotemporal, parietal, and occipital regions
- Concurrent DCD+ADHD correlated with poorer motor and attentional performance.





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Contrasting brain patterns of writing-related DTI parameters, fMRI connectivity, and DTI–fMRI connectivity correlations in children with and without dysgraphia or dyslexia

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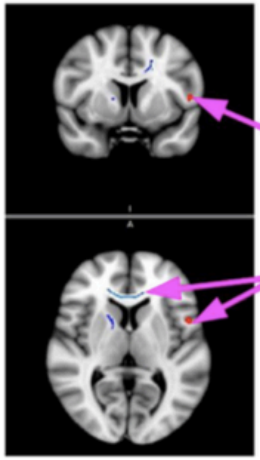
- Regions of reduced anisotropy in both dyslexia and dysgraphia groups :
  - anterior thalamus radiation and SLF,
  - left cingulum,
  - forceps minor.
- Regions of reduced anisotropy in dysgraphia : left cortico-spinal tract
- Regions of reduced anisotropy in dyslexia : right cortical spinal, bilateral inferior frontal occipital, and bilateral uncinate tracts

FMRI : connectivity at rest and during an orthographic task (children had to write a missing letter to create a word specific spelling)
  - dysgraphia : more connections from precuneus region,
  - dyslexia : more conections from left inferior temporo-occipital cortex (VWFA).

Overconnectivity is thought to reflect more effort necessary to execute the writing task.

Moreover : correlation between DTI anisotropy and FMRI connectivity

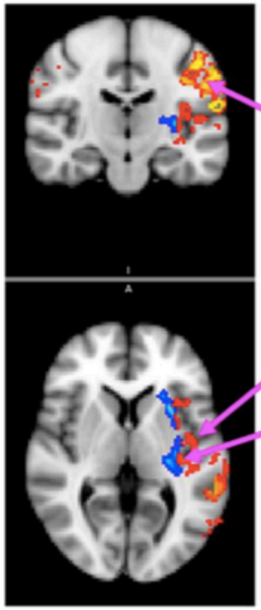
Comparing Dyslexic And Control Groups On DTI Relative Anisotropy And FMRI Connectivity



FMRI Connectivity Difference From Seed Region Occipital Temporal In Orange

DTI Relative Anisotropy Difference In Blue

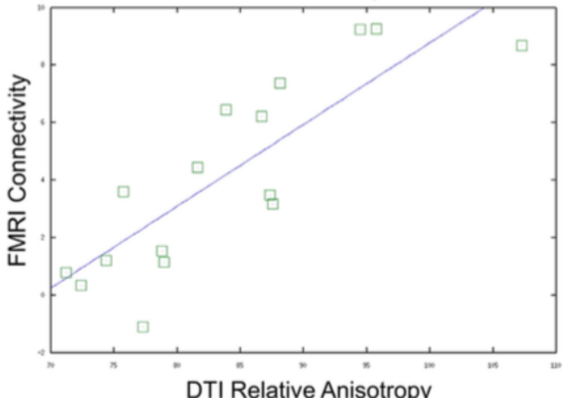
Dyslexia Versus Dysgraphia FMRI Connectivity and DTI



FMRI Connectivity Difference From Seed Occipital Temporal Region In Yellow/Orange

DTI Radial Diffusivity Difference In Blue

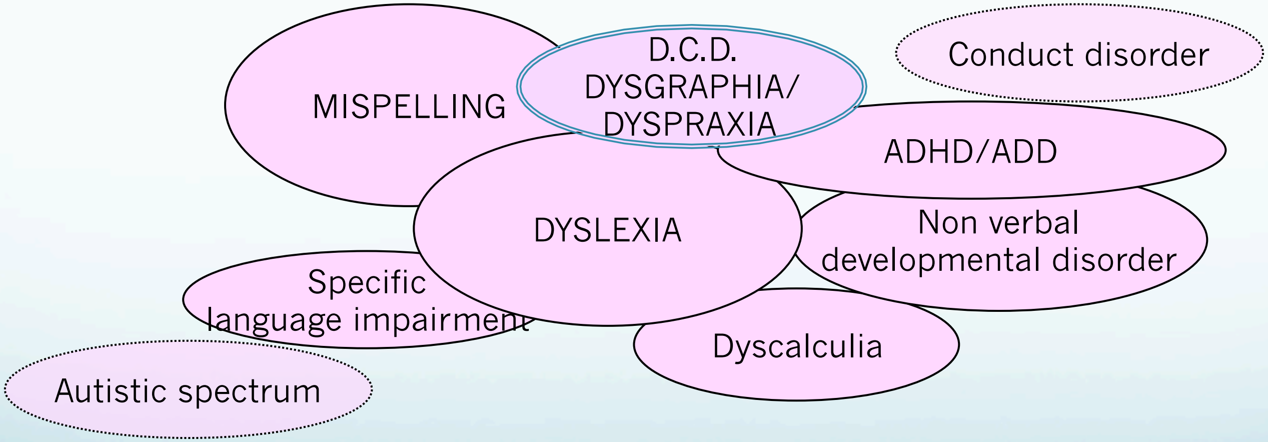
DTI/FMRI Connectivity Correlation



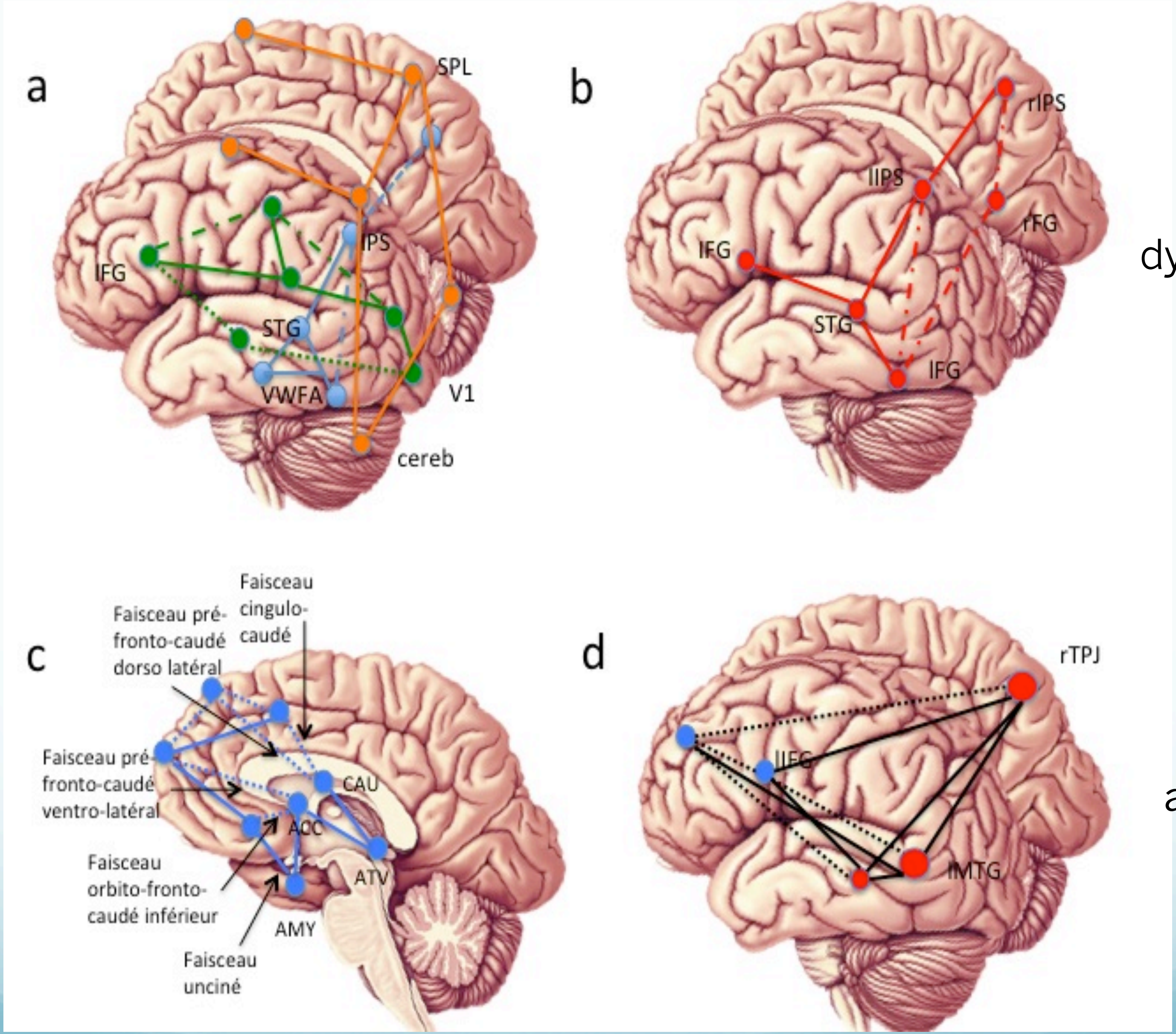
Brain imaging in DCD : summary

- Results from functional imaging are usually reported as ‘disappointing’, ‘scarce’ and ‘heterogeneous’
- Comorbidity with ADHD has often obscured interpretation of the data focusing on common motor outcomes rather than differences.
- Recently, studies of connectivity patterns have provided encouraging results, showing convincing, although again ubiquitous, alterations of several white matter tracts.

Part 3 : revisiting DCD in the context of learning disorders



IMPAIRED CONNECTIVITY IN NEURODEVELOPMENTAL DISORDERS

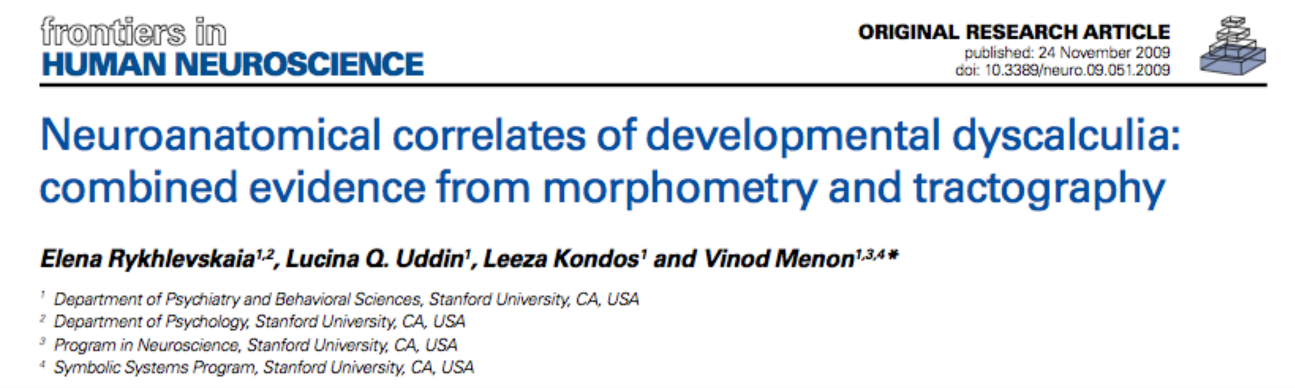


dyslexia

dyscalculia

ADHD

autism



frontiers in
HUMAN NEUROSCIENCE

ORIGINAL RESEARCH ARTICLE
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Neuroanatomical correlates of developmental dyscalculia: combined evidence from morphometry and tractography

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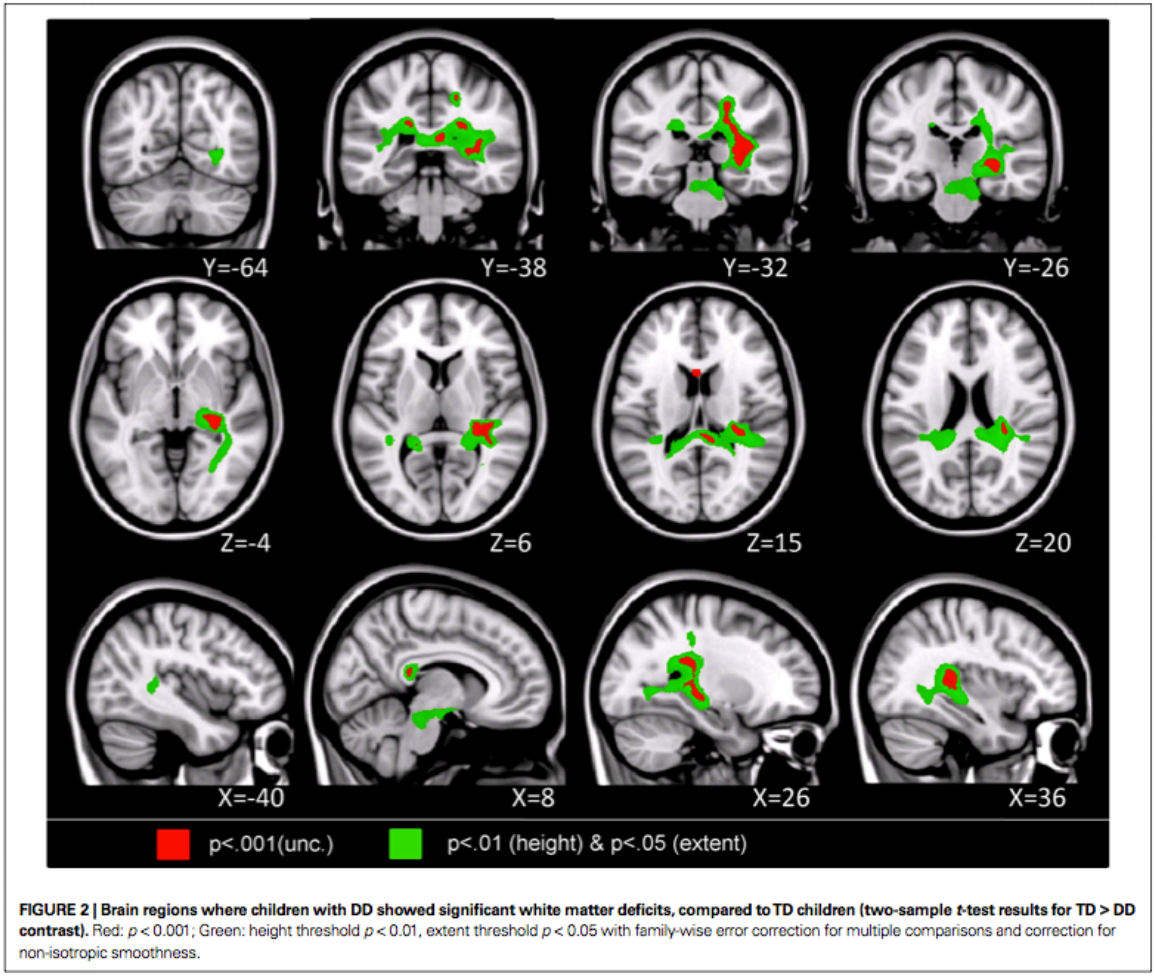
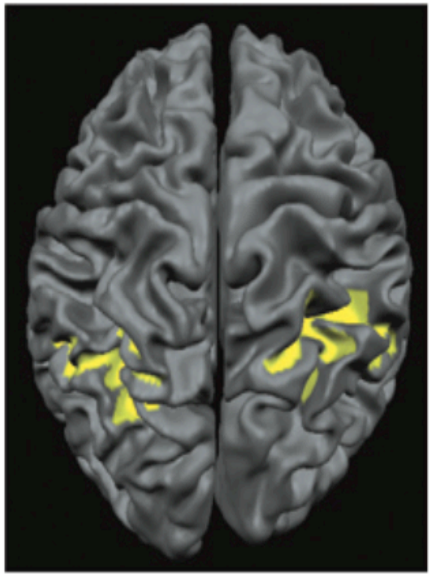
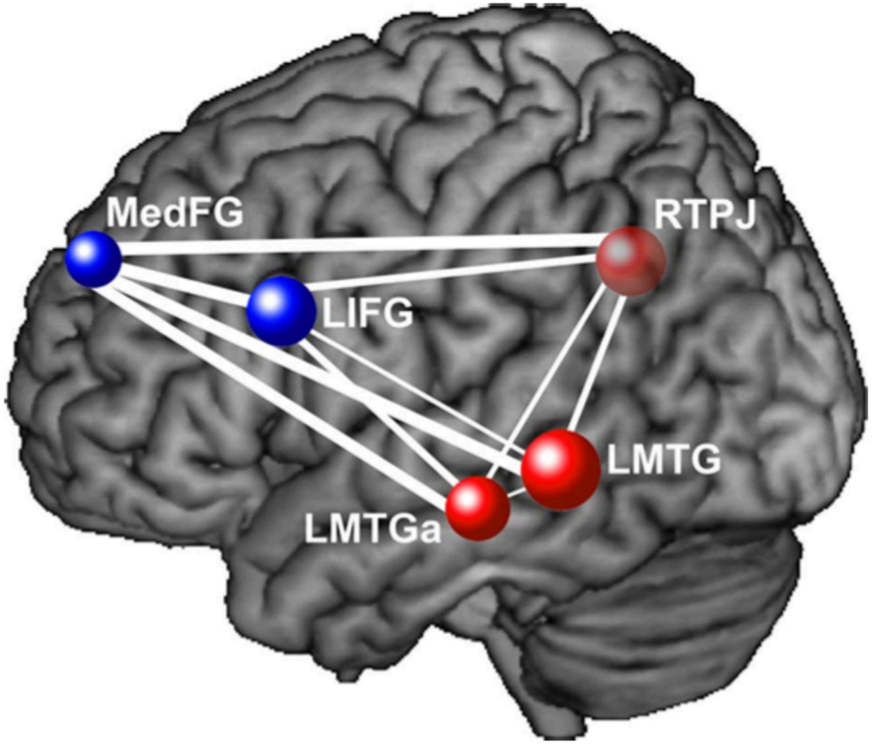


FIGURE 2 | Brain regions where children with DD showed significant white matter deficits, compared to TD children (two-sample *t*-test results for TD > DD contrast). Red: $p < 0.001$; Green: height threshold $p < 0.01$, extent threshold $p < 0.05$ with family-wise error correction for multiple comparisons and correction for non-isotropic smoothness.



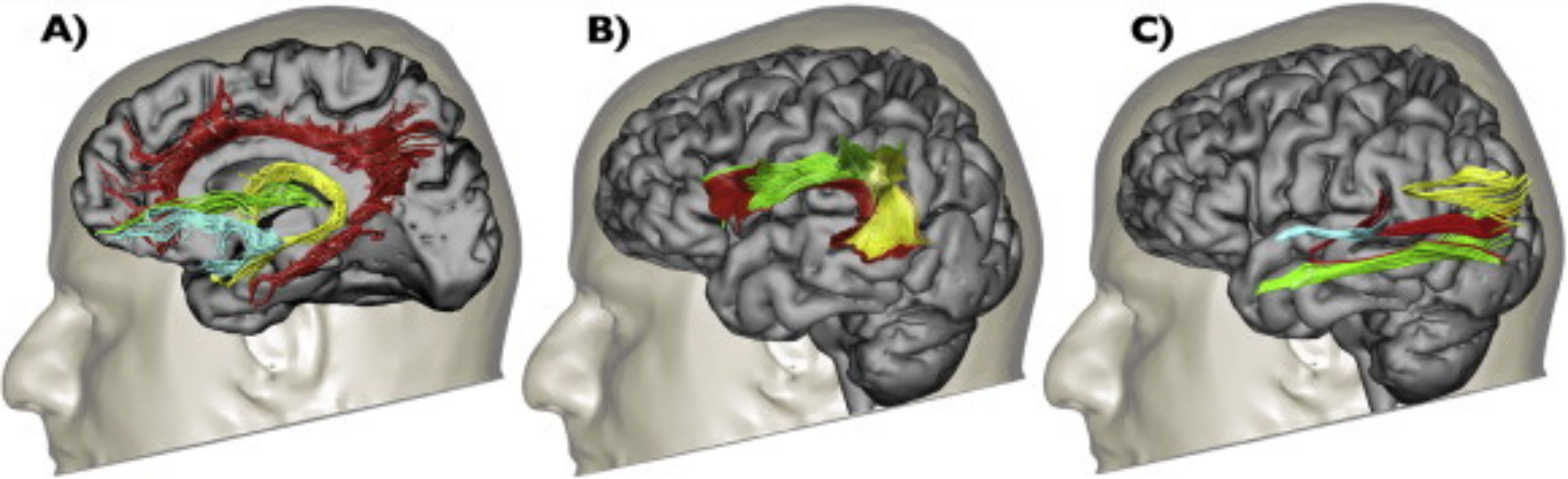
DTI tractography suggests that long-range WM projection fibers linking the right fusiform gyrus with temporal-parietal WM are a specific source of vulnerability in DD

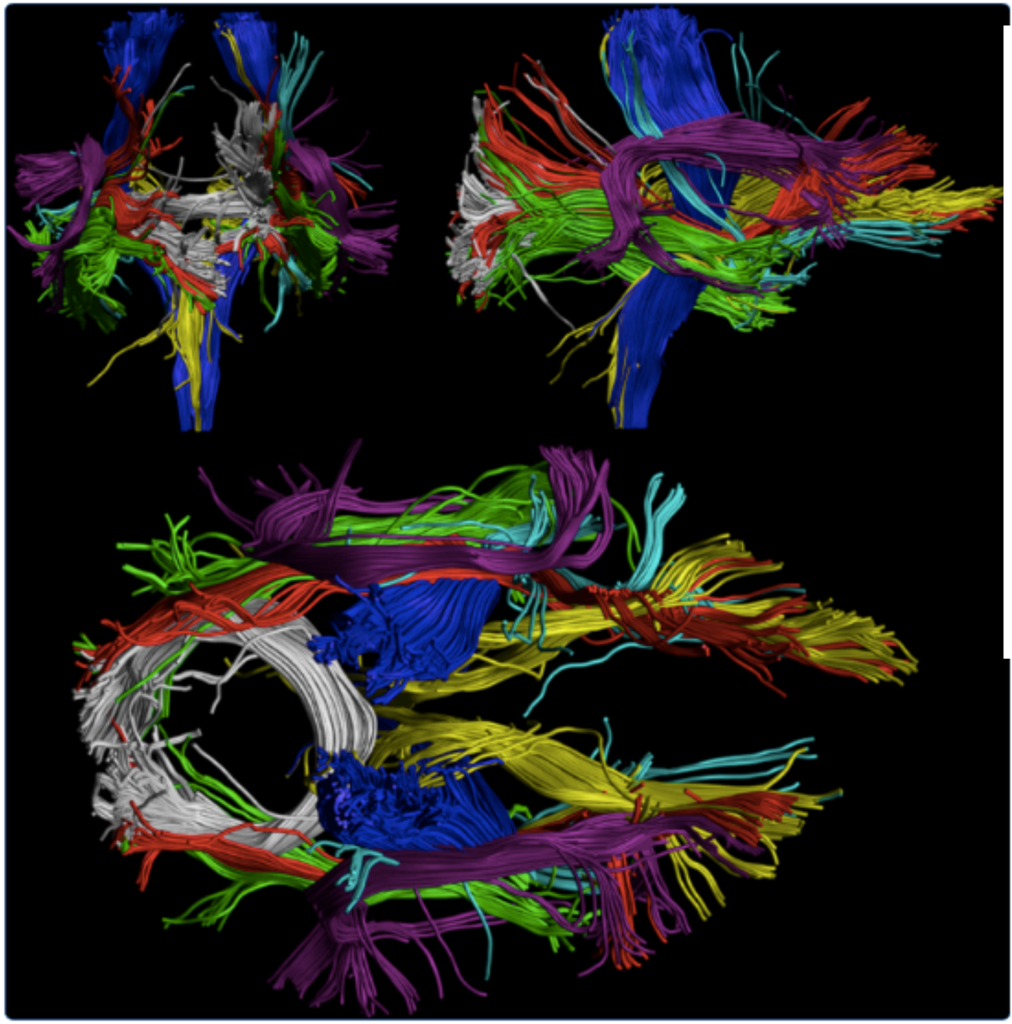


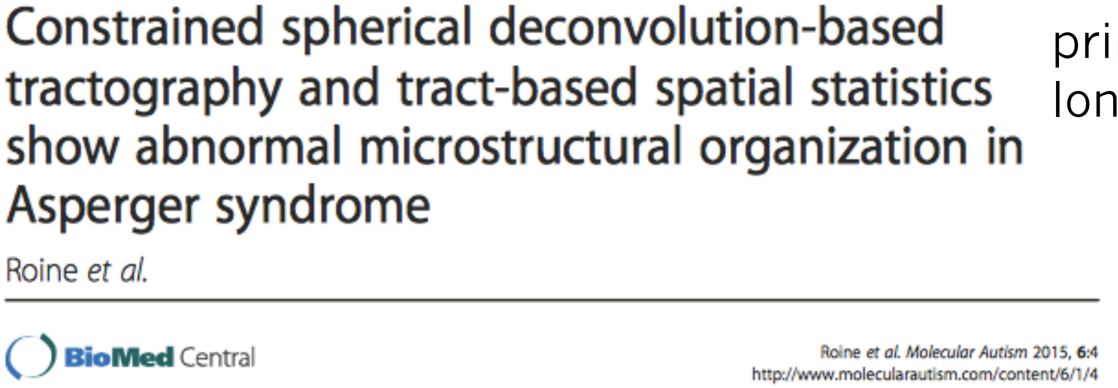
Autism : functional underconnectivity between frontal/posterior areas. Mason et al., 2008

AUTISM

White matter tracts of the socio-emotional processing system : A:limbic system; B:mirror neuron system; C: face processing system. Ameis & Catani, Cortex, 2015







Constrained spherical deconvolution-based tractography and tract-based spatial statistics show abnormal microstructural organization in Asperger syndrome

Roine *et al.*

BioMed Central

Roine *et al. Molecular Autism* 2015, **6**:4
http://www.molecularautism.com/content/6/1/4

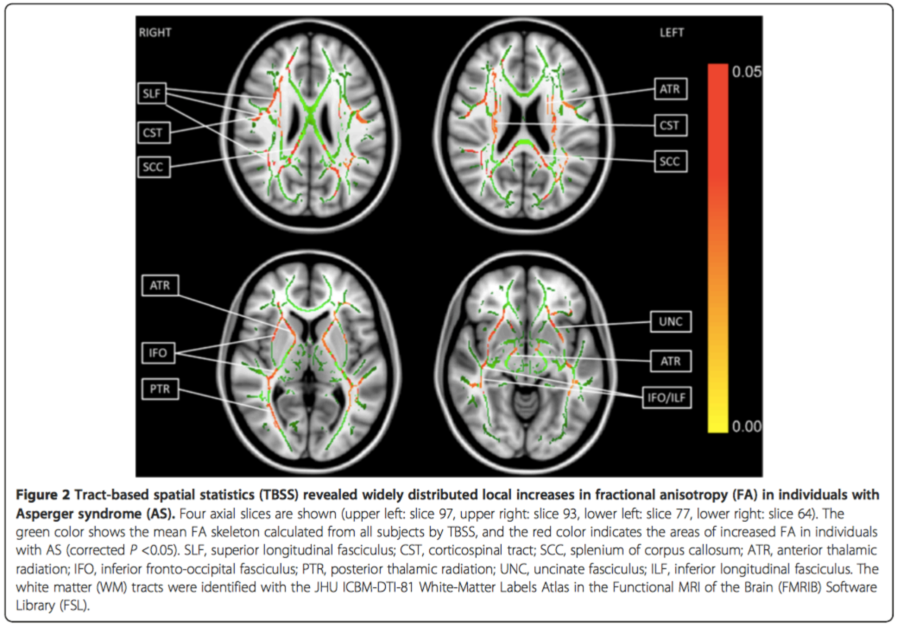
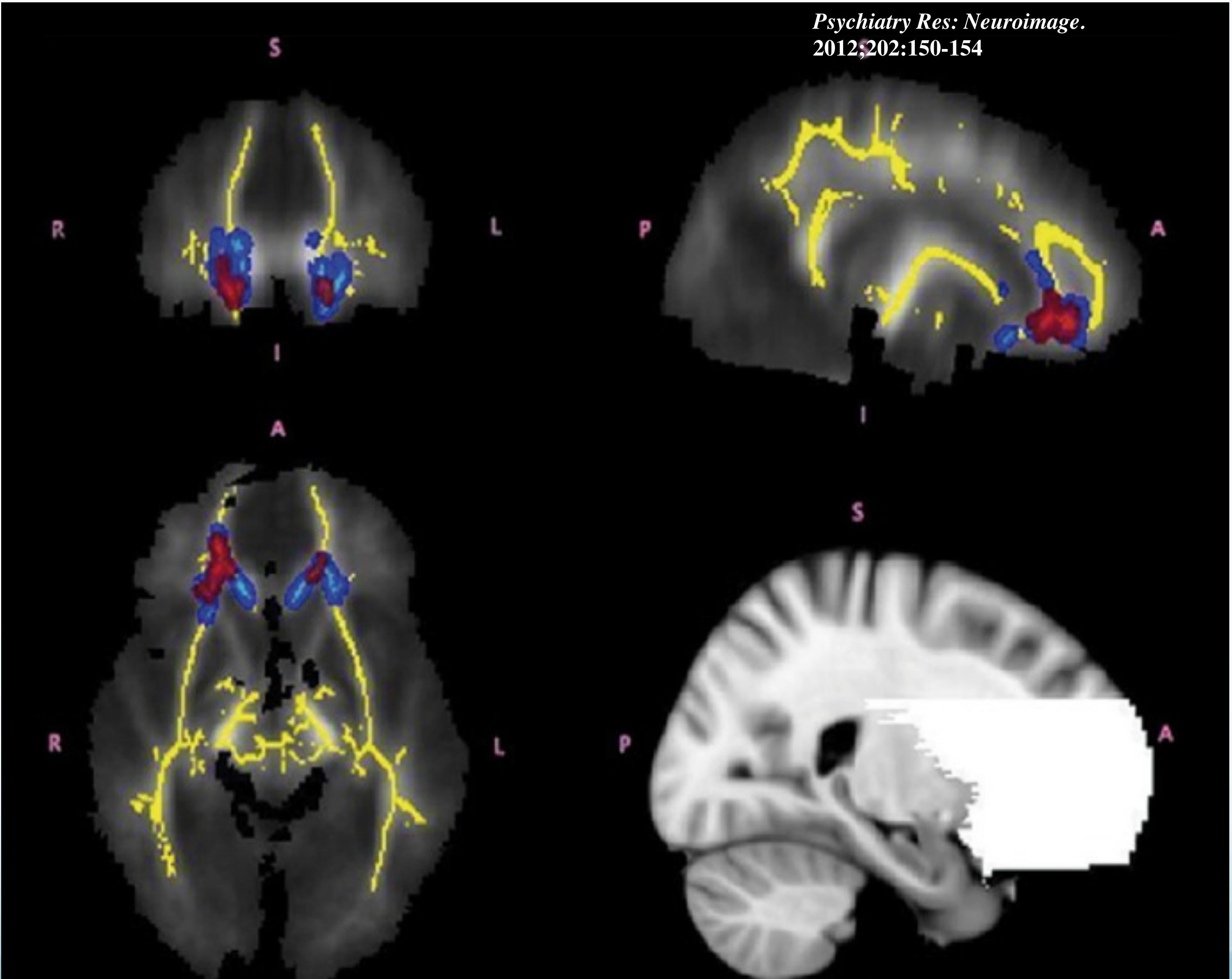


Figure 2 Tract-based spatial statistics (TBSS) revealed widely distributed local increases in fractional anisotropy (FA) in individuals with Asperger syndrome (AS). Four axial slices are shown (upper left: slice 97, upper right: slice 93, lower left: slice 77, lower right: slice 64). The green color shows the mean FA skeleton calculated from all subjects by TBSS, and the red color indicates the areas of increased FA in individuals with AS (corrected *P* <0.05). SLF, superior longitudinal fasciculus; CST, corticospinal tract; SCC, splenium of corpus callosum; ATR, anterior thalamic radiation; IFO, inferior fronto-occipital fasciculus; PTR, posterior thalamic radiation; UNC, uncinate fasciculus; ILF, inferior longitudinal fasciculus. The white matter (WM) tracts were identified with the JHU ICBM-DTI-81 White-Matter Labels Atlas in the Functional MRI of the Brain (FMRIB) Software Library (FSL).

14 H Asperger adultes, comparés à 19 témoins soigneusement sélectionnés, deux mesures d'anisotropie (FA) concordent pour montrer une augmentation de FA dans plusieurs faisceaux, principalement fronto-occipital et longitudinal inférieur gauche

Psychiatry Res: Neuroimage.
2012;202:150-154



DTI : **Regions of significant differences between adolescents with ADHD and controls**

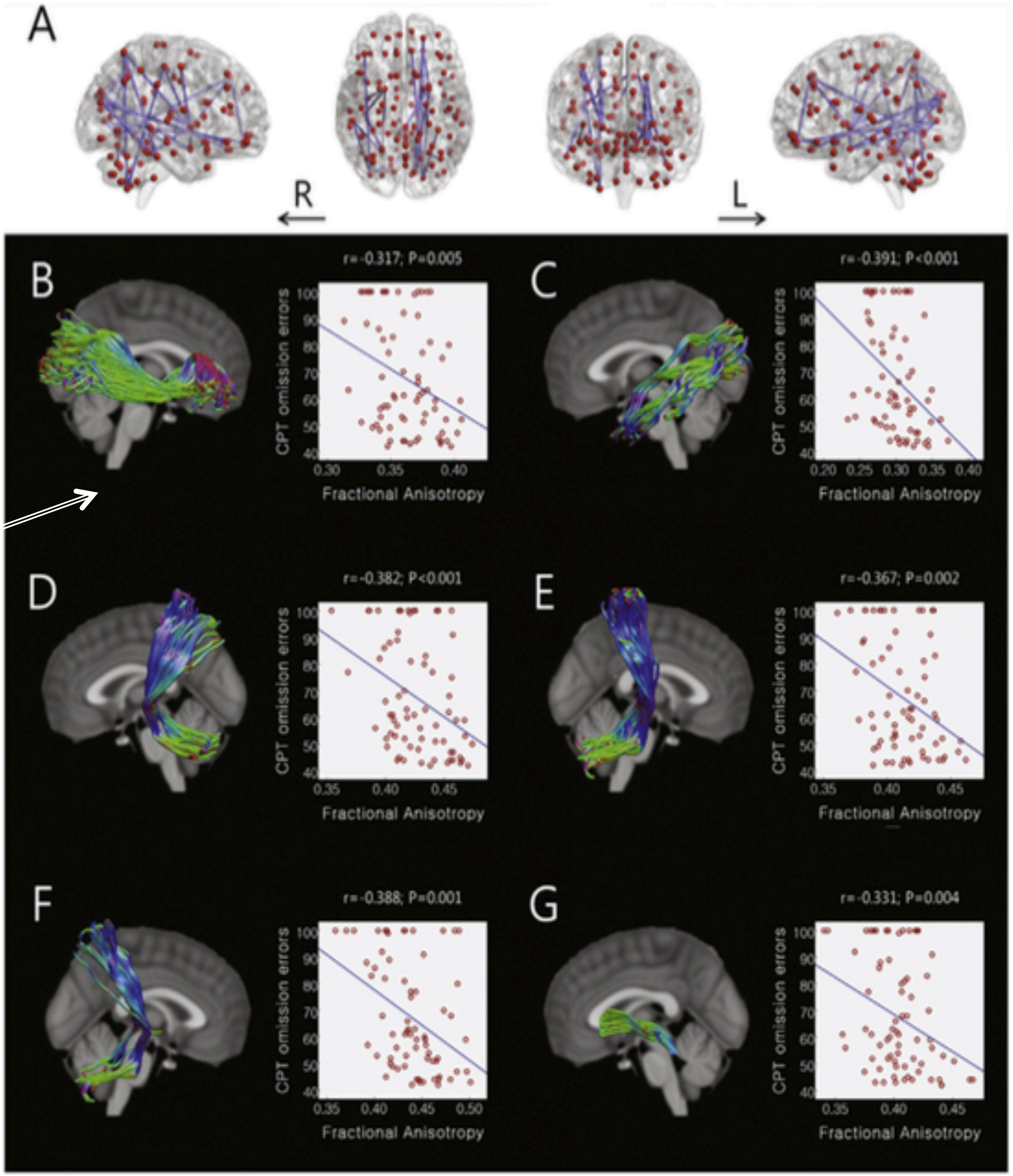
Connectomic Disturbances in Attention-Deficit/ Hyperactivity Disorder: A Whole-Brain Tractography Analysis

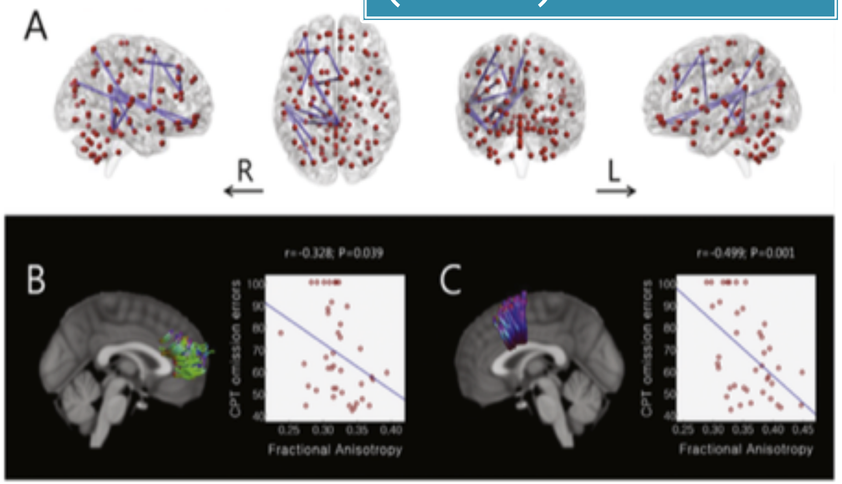
Soon-Beom Hong, Andrew Zalesky, Alex Fornito, Subin Park, Young-Hui
In-Chan Song, Chul-Ho Sohn, Min-Sup Shin, Bung-Nyun Kim, Soo-Churl
Jae Hoon Cheong, and Jae-Won Kim

Corrélation entre défaut de connectivité dans divers faisceaux d’association et nombre d’erreurs d’omission au CPT2

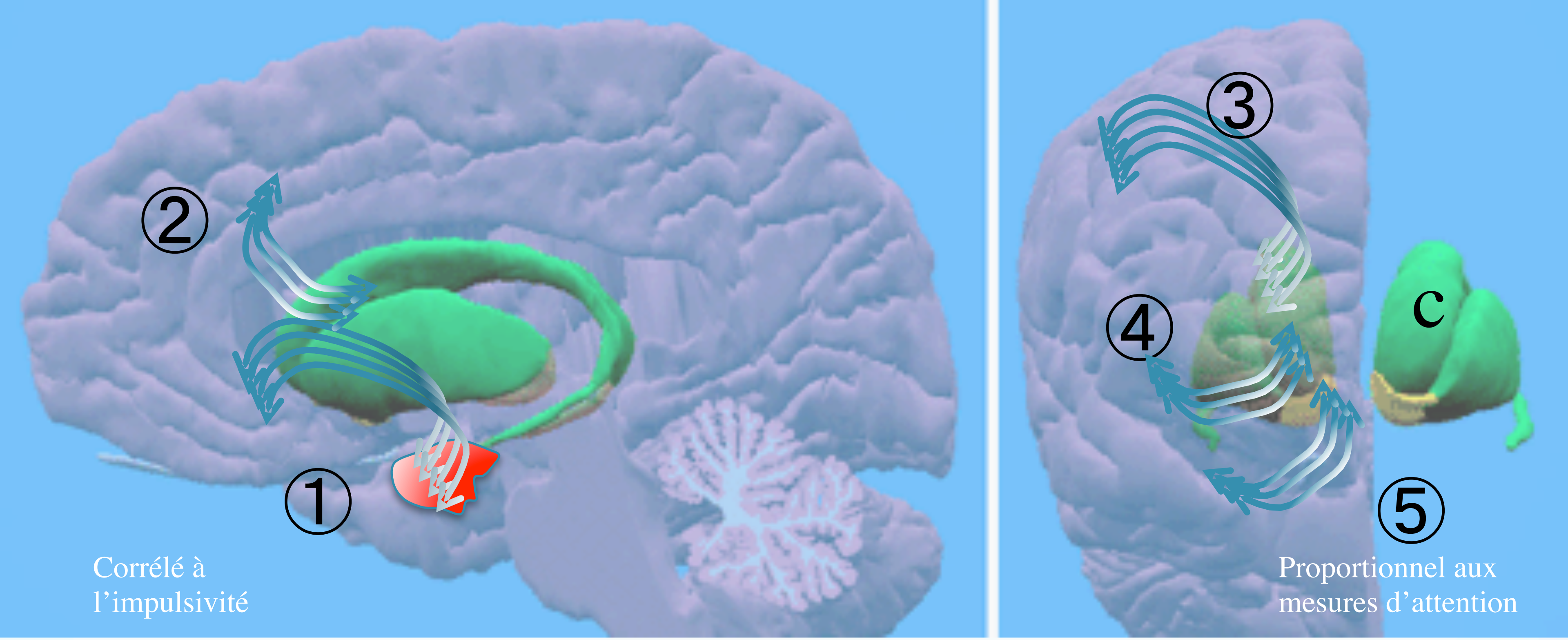
ADHD, combined (n=39)

ADHD, inattentive (n=26)





BIOL PSYCHIATRY 2014;76:656–663

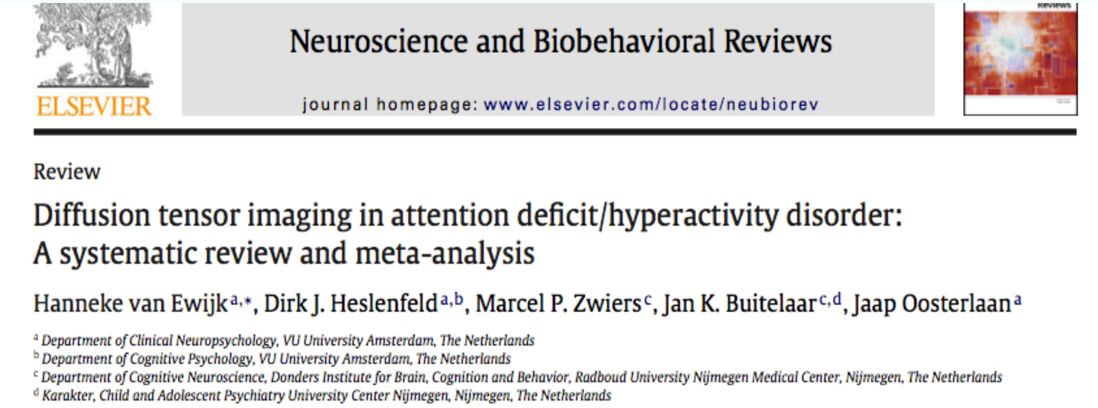


Corrélé à l’impulsivité

Proportionnel aux mesures d’attention

- TDAH :schématisation des principaux faisceaux d’association issus du cortex frontal tels qu’ils peuvent être individualisés en tractographie IRM.
- **anomalie d’anisotropie en tractographie** proportionnelle à diverses mesures des fonctions exécutives (mémoire de travail, attention soutenue, flexibilité...)

4, 5 : fronto-strié ventro-latéral et orbito-caudé : corrélés au déficit attentionnel
1 : unciné : corrélé à l’impulsivité
D’après Chang et al. (2012); Wu et al. (2012)



Neuroscience and Biobehavioral Reviews

journal homepage: www.elsevier.com/locate/neubiorev

Review

Diffusion tensor imaging in attention deficit/hyperactivity disorder: A systematic review and meta-analysis

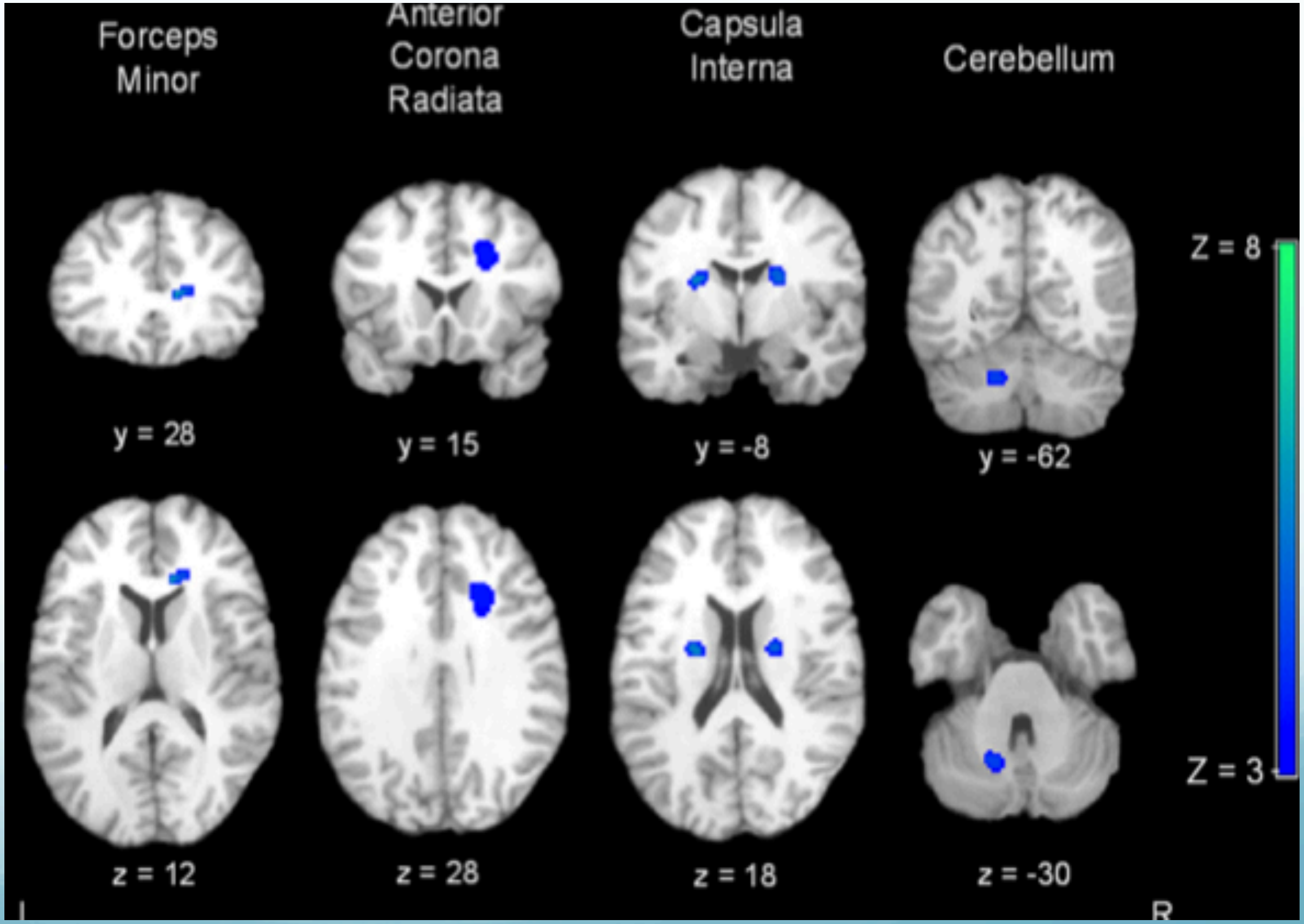
Hanneke van Ewijk[a,*], Dirk J. Heslenfeld[a,b], Marcel P. Zwiers[c], Jan K. Buitelaar[c,d], Jaap Oosterlaan[a]

[a] Department of Clinical Neuropsychology, VU University Amsterdam, The Netherlands
[b] Department of Cognitive Psychology, VU University Amsterdam, The Netherlands
[c] Department of Cognitive Neuroscience, Donders Institute for Brain, Cognition and Behavior, Radboud University Nijmegen Medical Center, Nijmegen, The Netherlands
[d] Karakter, Child and Adolescent Psychiatry University Center Nijmegen, Nijmegen, The Netherlands

« ALE » Meta-analysis of 15 DTI studies published until 2011:173 ADHD patients and 169 healthy control subjects

Decreased anisotropy

- sup. long. fasci
- cortico-spinal f.
- fronto-striatal connections
- Left cerebellum



Trouble d'apprentissage non-verbal : études en IRM

- 31 controls, 29 NVLD, 29 AS
- Volumetric study with IRM T1 :
- gray matter, white matter, cerebrospinal fluid (CSF), amygdala, hippocampus, and anterior cingulate cortex (ACC)
- AS : larger hippocampal and amygdala volumes than the other groups
- AS & NVLD, ACC << control

Semrud-Clikeman et al., *J Clin Exp Neuropsychol*. 2013;35(5): 540-50

4 groups : NVLD; n = 19 , high-functioning autism (HFA; n = 23), predominantly inattentive ADHD (ADHD:PI; n = 23), combined type ADHD (ADHD:C; n = 25), typical development (n = 57).

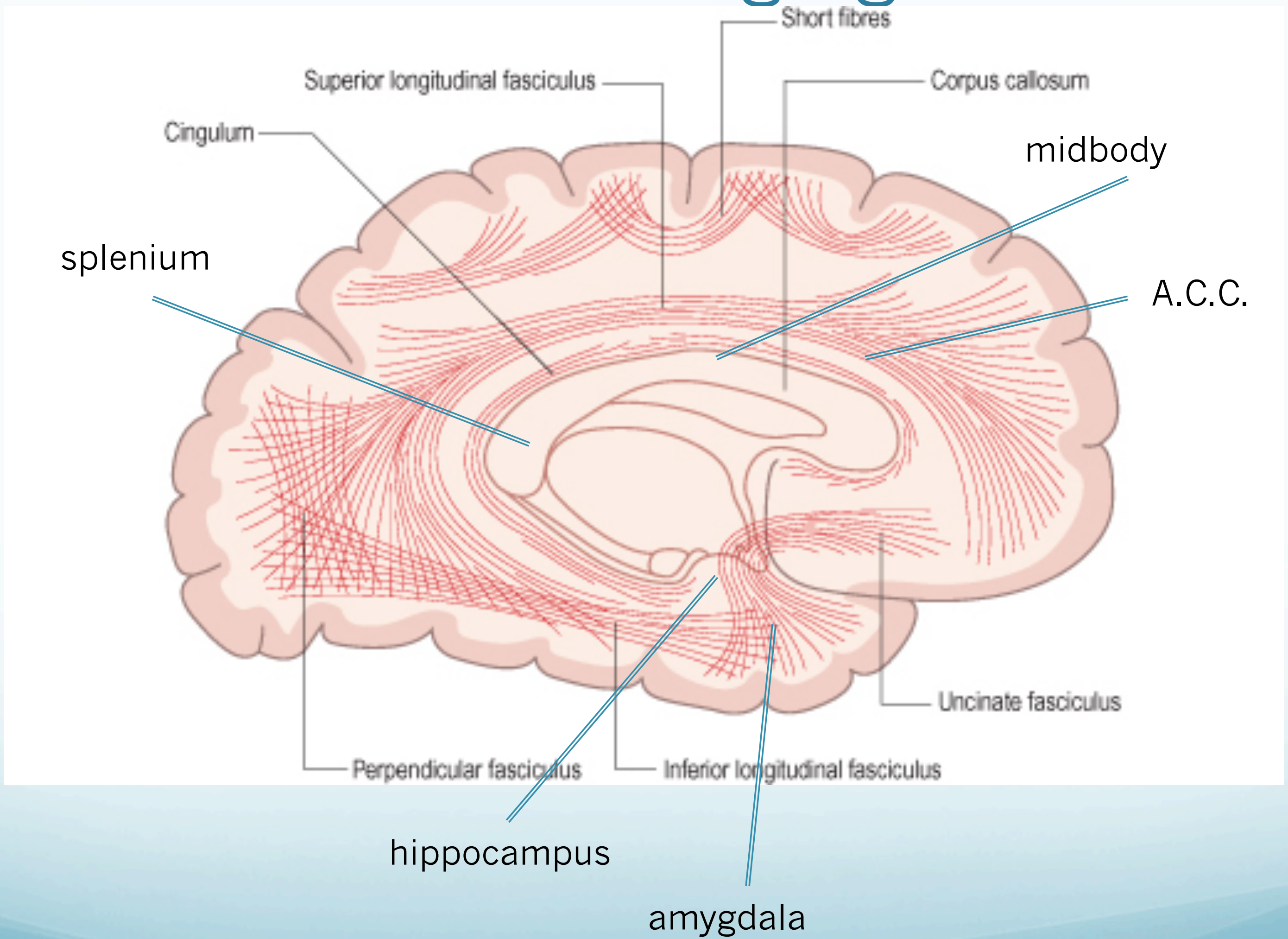
Measurement and segmentation of corpus callosum (cf Witelson, 1989)

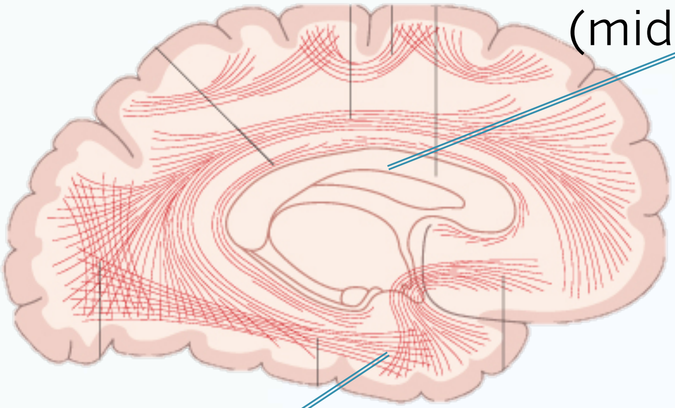
HFA : larger midbody area

NVLD : smaller splenium than all other groups, associated with lower PIQ

Fine et al., *Child Neuro-psychology*, 201420:6, 641-661

Nonverbal learning disabilities : summary of two brain imaging studies



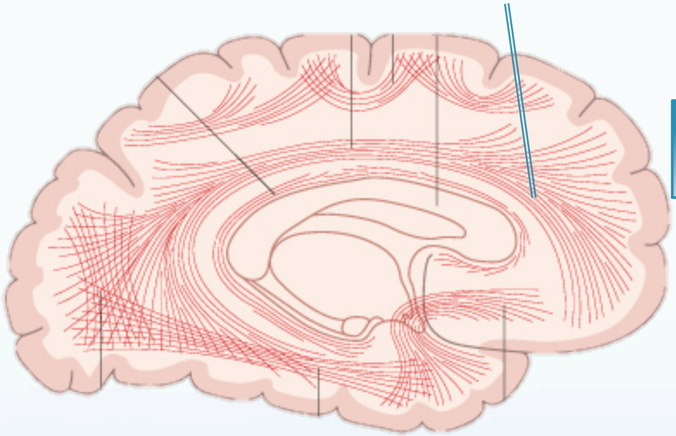


> Corpus callosum
(midbody)

Autism/Asperger
only

>> amygdala
+
hippocampus

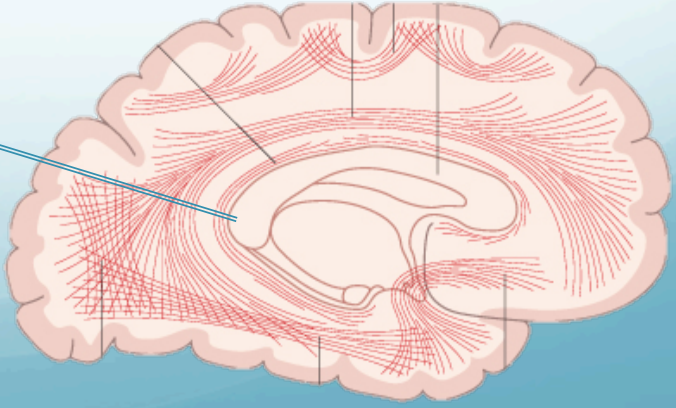
< ACC

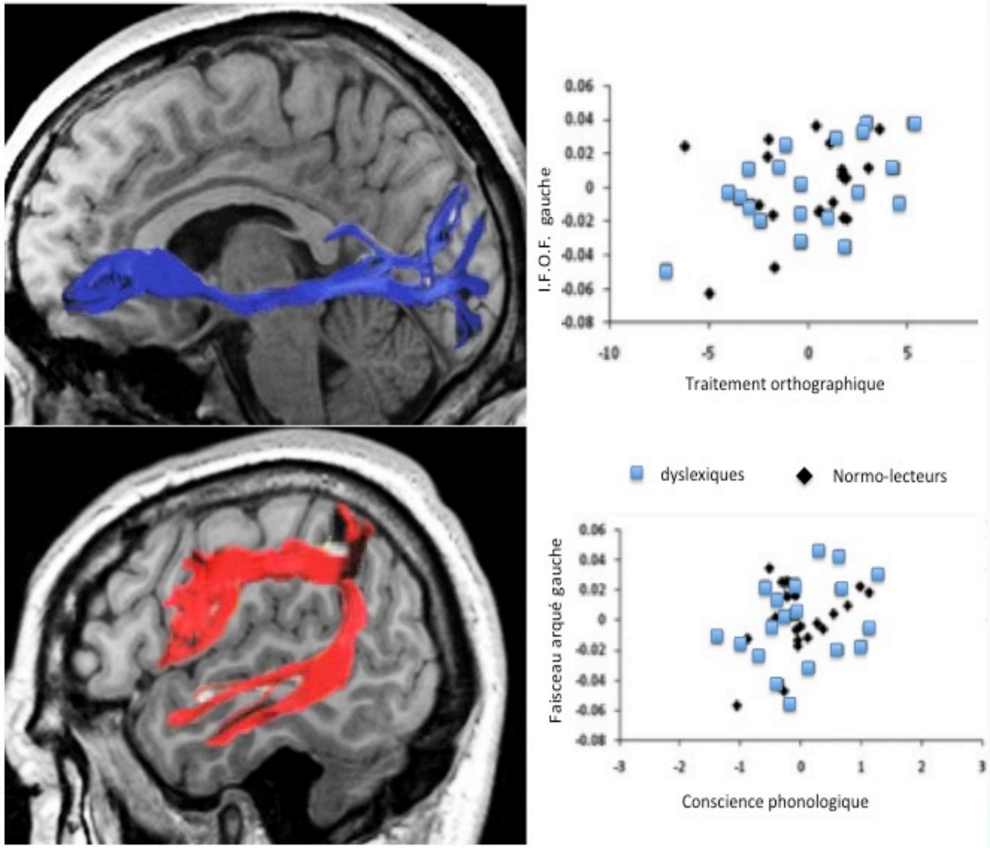


NVLD = Asperger

< splenium

NVLD only





I.F.O.F. : orthography

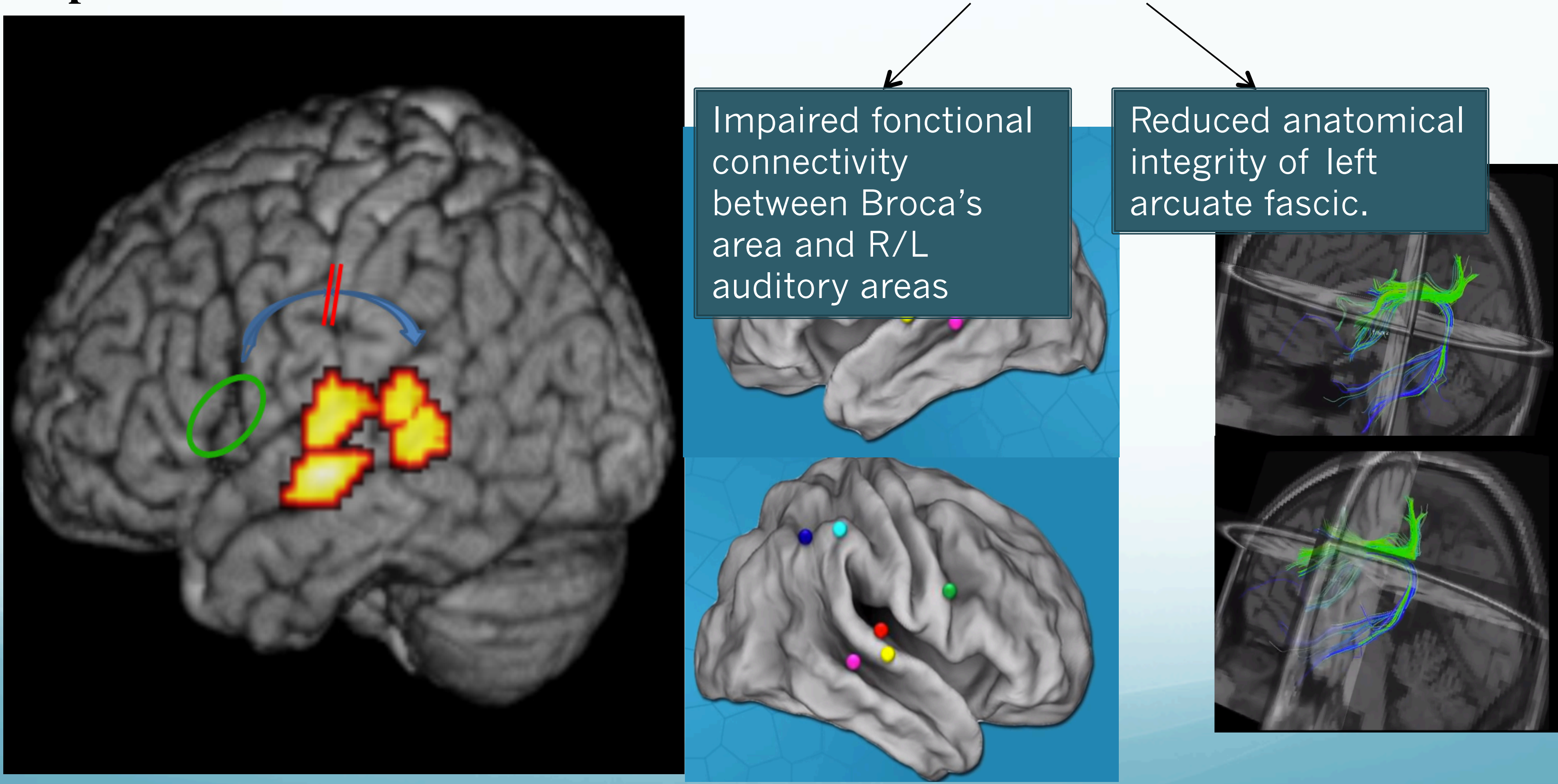
Arcuate fasciculus : phonology

From Vandermosten et al., 2012.

Boets et al., 2013:

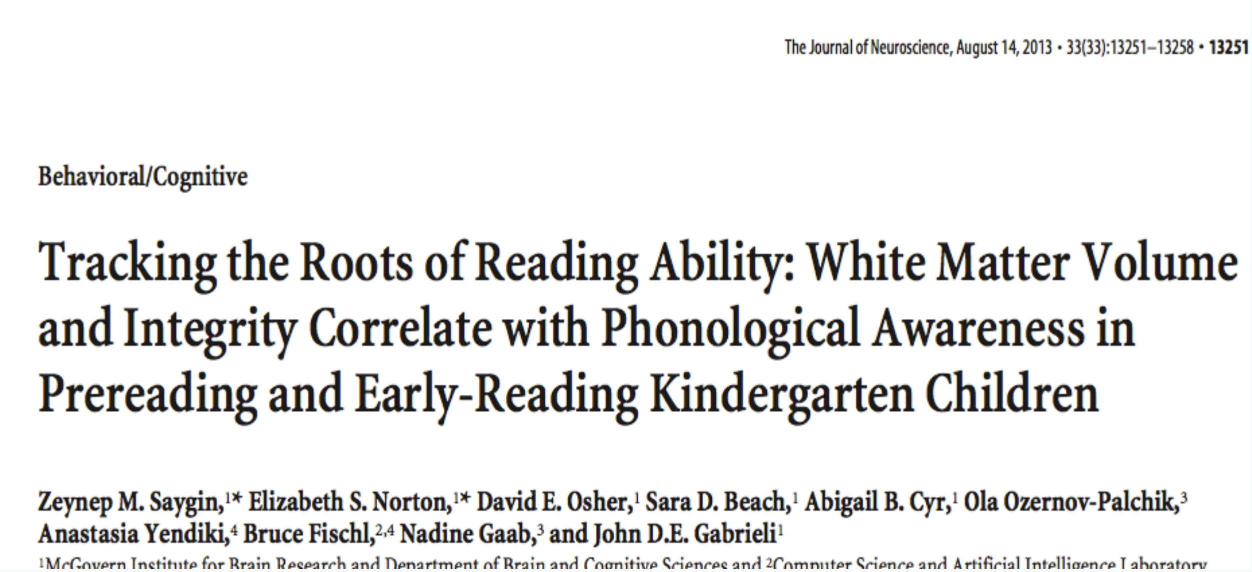
- les corrélations sont plus fortes au sein d'une catégorie qu'entre les catégories : signe la robustesse des représentations

- phonemic representations are as robust in DYS as in NORM : they are not degraded as previously thought → DYS people have a problem of **access to otherwise intact representations**



Impaired fonctional connectivity between Broca's area and R/L auditory areas

Reduced anatomical integrity of left arcuate fascic.



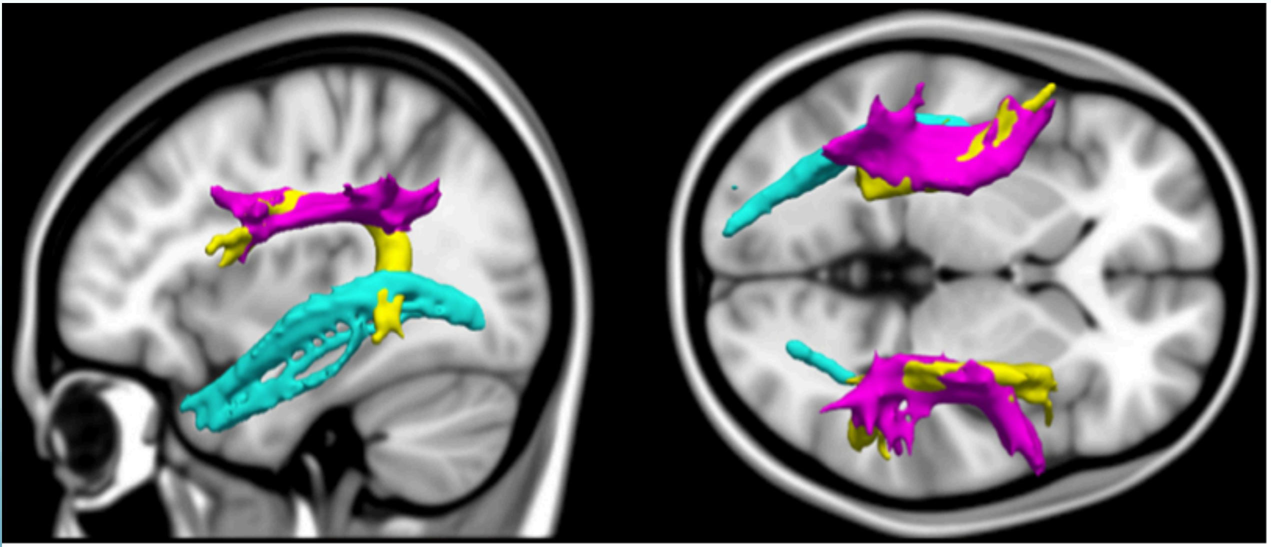
The Journal of Neuroscience, August 14, 2013 • 33(33):13251–13258 • 13251

Behavioral/Cognitive

Tracking the Roots of Reading Ability: White Matter Volume and Integrity Correlate with Phonological Awareness in Prereading and Early-Reading Kindergarten Children

Zeynep M. Saygin,[1]* Elizabeth S. Norton,[1]* David E. Osher,[1] Sara D. Beach,[1] Abigail B. Cyr,[1] Ola Ozernov-Palchik,[3] Anastasia Yendiki,[4] Bruce Fischl,[2,4] Nadine Gaab,[3] and John D.E. Gabrieli[1]

[1]McGovern Institute for Brain Research and Department of Brain and Cognitive Sciences and [2]Computer Science and Artificial Intelligence Laboratory



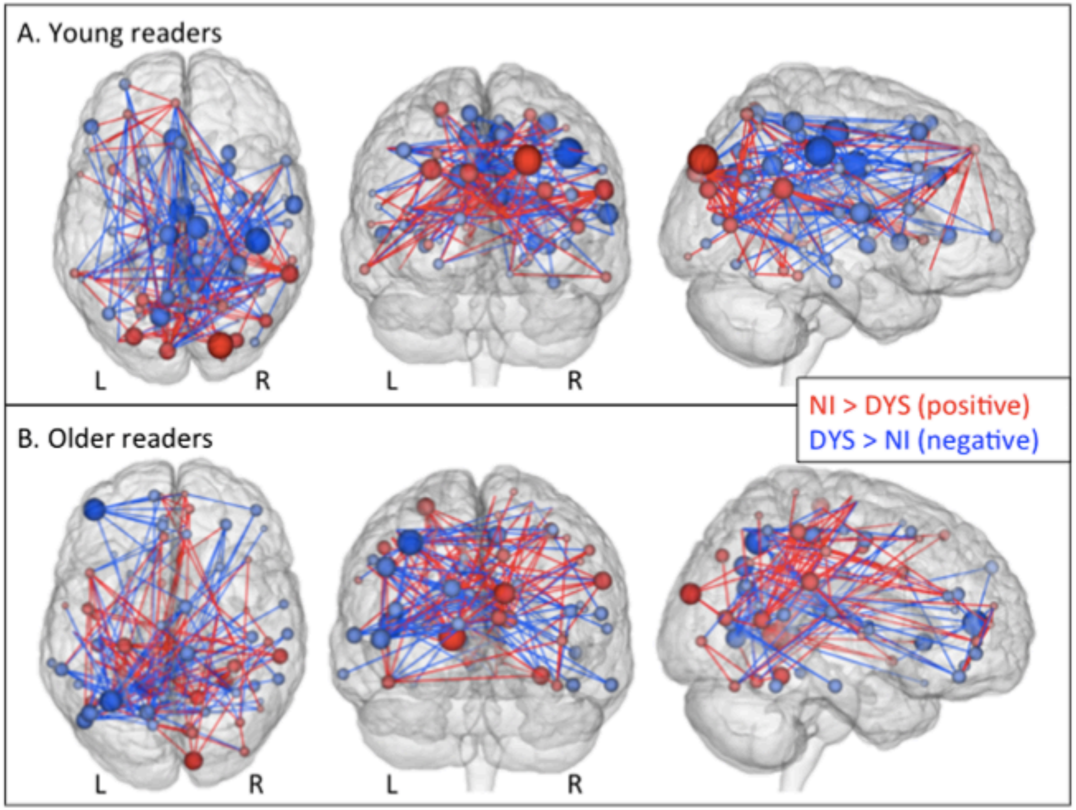
In kindergarten children, we found a correlation between phonological awareness for spoken language and indices of white matter organization of the left arcuate fasciculus, specifically volume and FA. This relationship was both anatomically and behaviorally specific; it was not observed in other tracts (left ILF, left SLFp, or right hemisphere homologs) or for other behavioral predictors of dyslexia. These results were observed in the whole group of 40 children with varied reading abilities in the first half of kindergarten and also in the subset of 18 children who were prereaders. The specific relation between phonological awareness and the left arcuate fasciculus was corroborated by an independent whole-brain analysis. The discovery that such a relation between white matter organization and one of the strongest behavioral predictors of dyslexia, poor phonological awareness, exists before formal reading instruction and substantial reading experience favors the view **that differences in white matter organization are not only the consequence of dyslexia, but also may be a cause of dyslexia.**

ARCHIVAL REPORT

Disruption of Functional Networks in Dyslexia: A Whole-Brain, Data-Driven Analysis of Connectivity

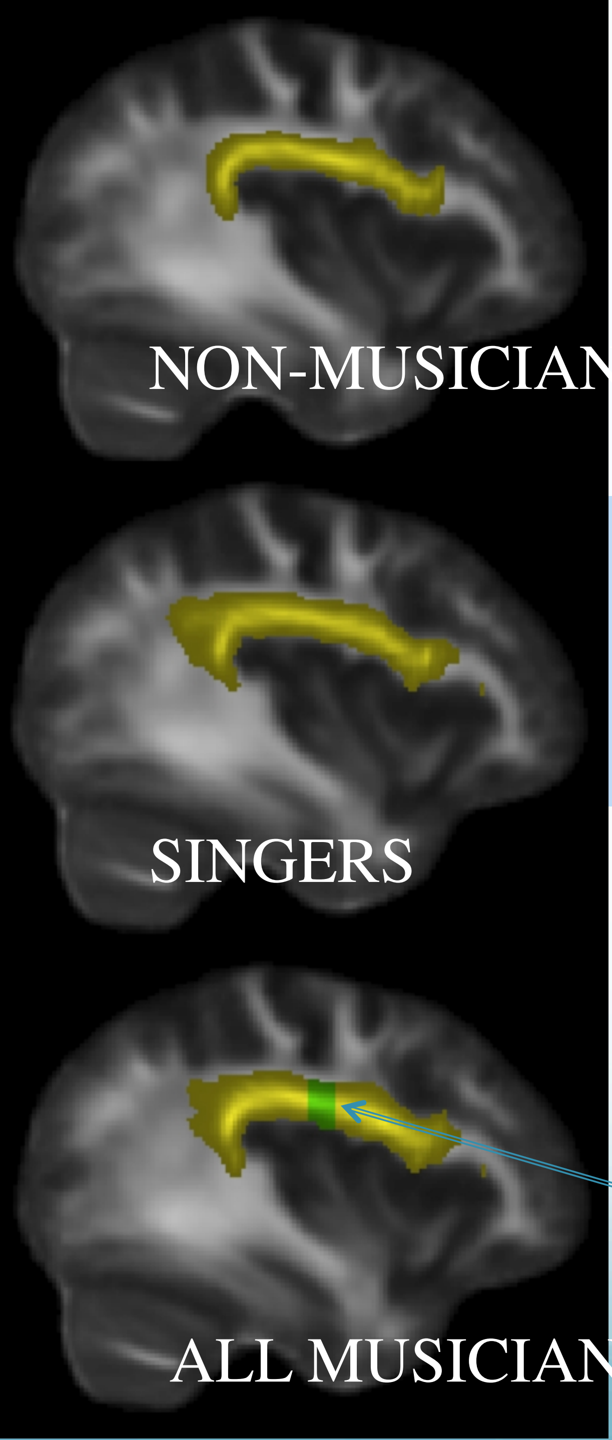
Emily S. Finn, Xilin Shen, John M. Holahan, Dustin Scheinost, Cheryl Lacadie,
Xenophon Papademetris, Sally E. Shaywitz, Bennett A. Shaywitz, and R. Todd Constable

400 BIOL PSYCHIATRY 2014;76:397–404



Compared to NI readers, DYS readers showed divergent connectivity within the visual pathway and between visual association areas and prefrontal attention areas; increased right-hemisphere connectivity; reduced connectivity in the visual word-form area; and persistent connectivity to anterior language regions around the inferior frontal gyrus.

Our findings indicate that there is not yet a significant discrepancy in VWFA connectivity between dyslexic and younger good readers but that the gap widens with age as good readers reach "expert" status.

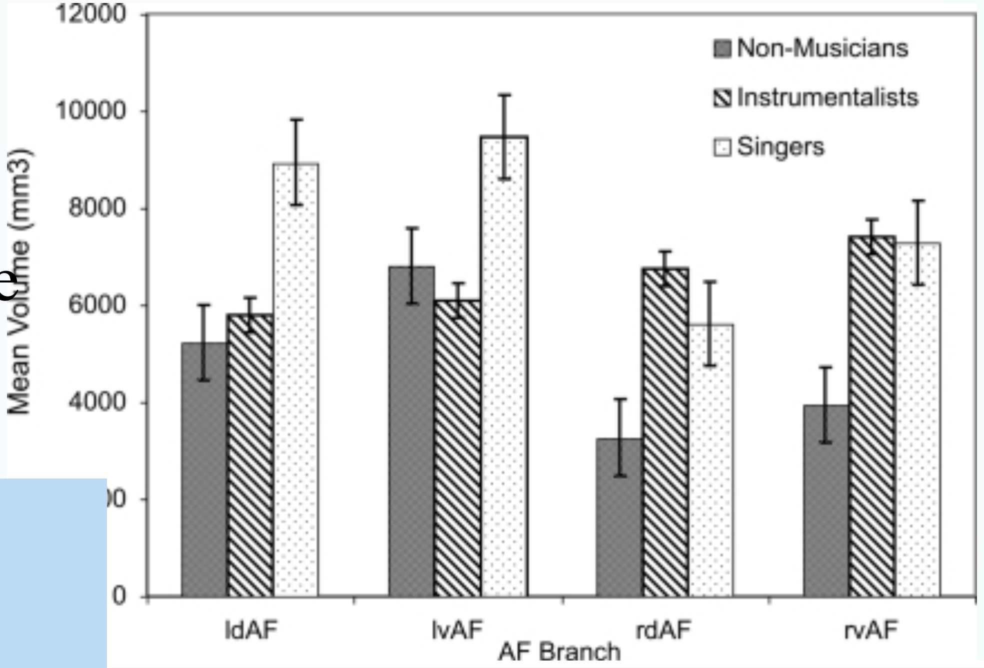


NON-MUSICIANS

SINGERS

ALL MUSICIANS

Volume



Differences mainly in left arcuate fasciculus, dorsal part

anisotropy

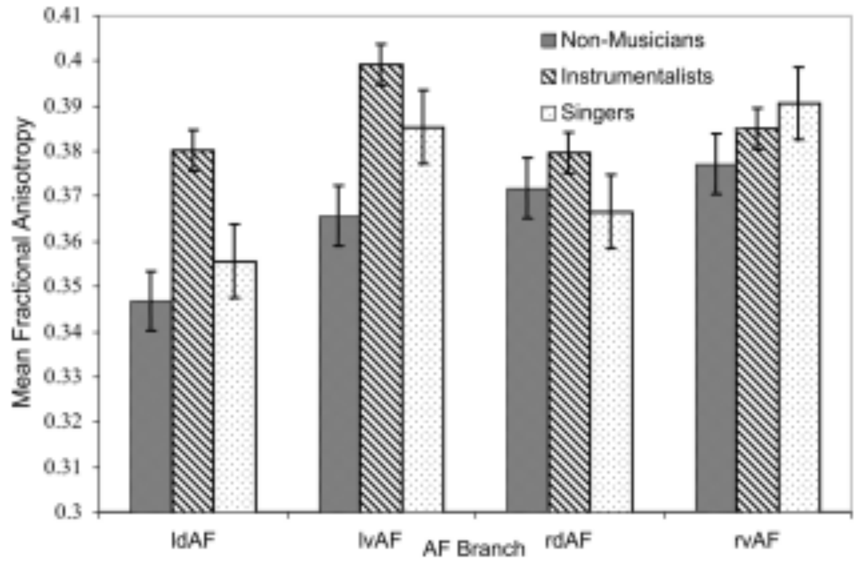
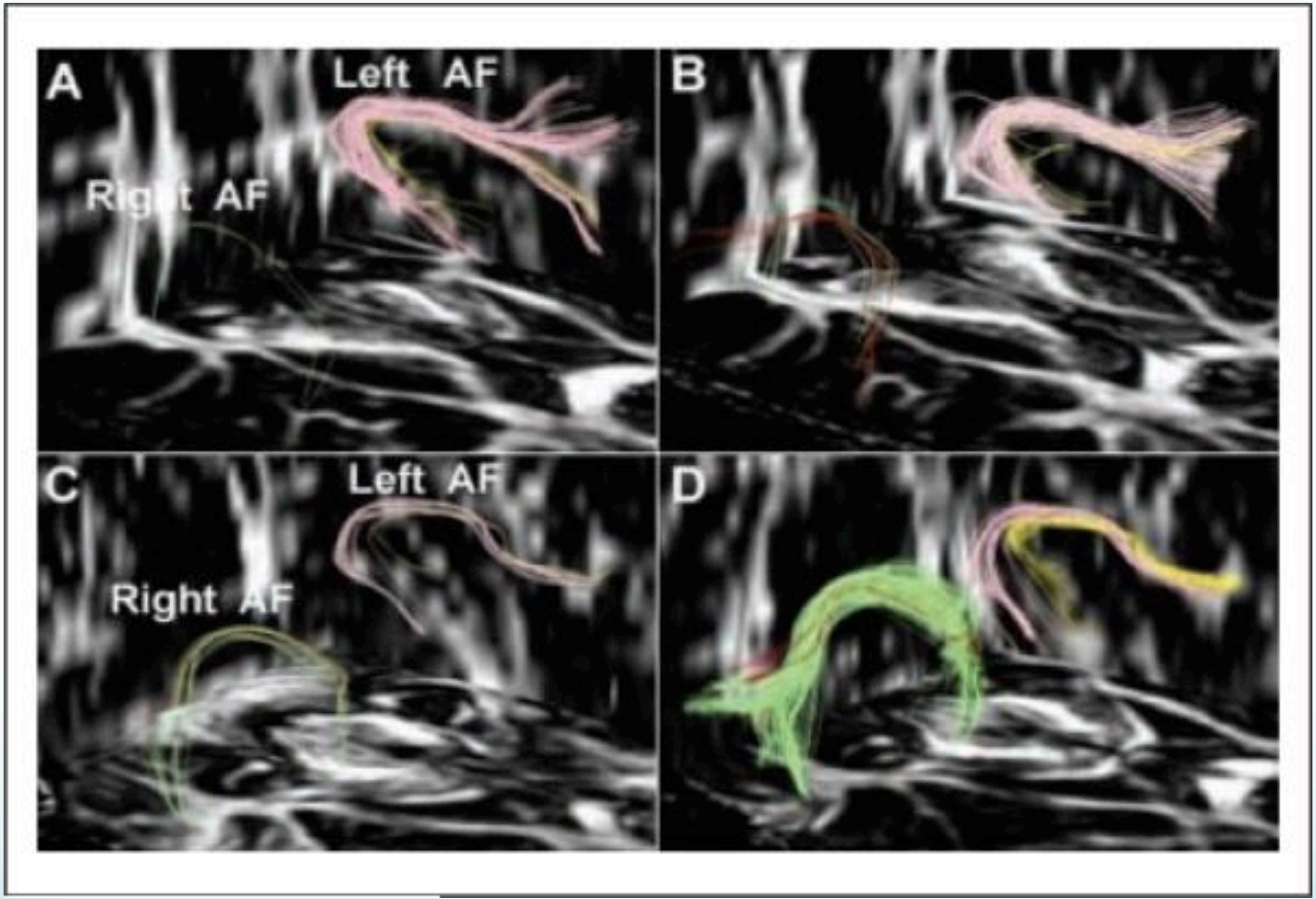


FIGURE 3 | Mean FA for all branches of the AF in both hemispheres for all groups (l = left, r = right, d = dorsal, v = ventral). Error bars represent SE of the mean.

Zone of main difference anisotropy

8-year-old child without instrumental music training scanned twice (A and B) 2 years apart



8-year-old child before (C) and 2 years after (D) instrumental music training involving a string instrument.

Changes in the arcuate fasciculus after instrumental music training (Schlaug et al., 2013)

In conclusion

- The clinical polymorphism and multiple comorbidities of DCD strongly suggest to consider this condition within the realm of neurodevelopmental disorders.
- There is now converging evidence that a common feature to all these conditions, including DCD, could be found at the level of long-distance connectivity, and that various associations and comorbidities could be conceptualized in terms of altered white matter connections
- This could be one major avenue in the future for research on DCD, with two main directions : better understanding of associations, but also better comprehension of each clinical component of the syndrome.