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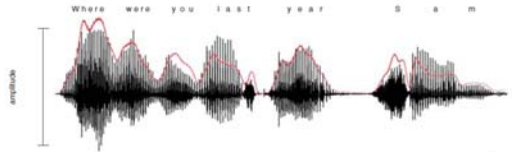
The auditory temporal processing theory about dyslexia: behavioral and neural evidence

Pol Ghesquière

Also on behalf of the Dyslexia Research Collaboration (DYSCO) team of KU Leuven

Underlying rationale

- Sound = vibrations with a specific frequency and amplitude
- ***Speech perception*** requires adequate tracking of rapid transitions in frequency and amplitude (***auditory temporal processing*** of dynamic stimuli)



- Speech perception may be the basis of good ***phonological representations*** / phonological awareness

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Cognitive causes of dyslexia

- Central theory:

  Phonological deficit theory
  - Phonological Awareness (PA)
    - rime awareness
    - syllable awareness
    - phoneme awareness
    - the quality of the mental representation of phonemes determines the quality of the development of grapheme-phoneme connections
      - important for reading via decoding
  - Rapid Automatized Naming (RAN)
    - the speed of retrieving *'phonological codes'* determines the speed of word recognition
      - important for reading via direct word recognition
  - Verbal Short Term Memory (VSTM)

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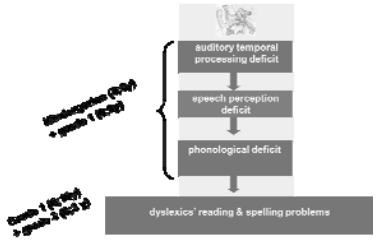
Longitudinal study (PhD Bart Boets)

- Prospective longitudinal family-risk study
  - first data collection before children were able to read
  - continuous registration of the developmental pathway



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AUDITORY TEMPORAL PROCESSING DEFICIT HYPOTHESIS

auditory temporal deficit

speech perception deficit

phonological deficit

reading and spelling problems

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Participants

- Target group
  - 31 high family-risk for dyslexia (HR) pre-readers (18 m / 13 f)
    - at least one first-degree relative diagnosed as dyslexic
    - Age = five years (last year of kindergarten)
    - Native Dutch speakers
    - No history of brain damage, articulatory problems, long term hearing loss or visual problems
- Control group
  - 31 low family risk for dyslexia (LR) pre-readers (18 m / 13 f)
    - no known family members with learning or language problems
    - Native Dutch speakers
    - Same exclusion criteria
- Matched for
  - Educational environment, i.e. same school
  - Sex
  - Age
  - Non-verbal IQ
  - Educational level of mother and father

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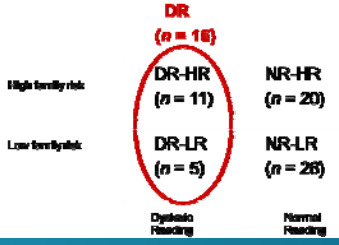
Defining reading groups

- Dyslexic Reading group (DR)
  - Severe and persistent reading and/or spelling problems
  - Scoring below Pc 10 on the standardized word reading and/or spelling test in grade 1 and in grade 3



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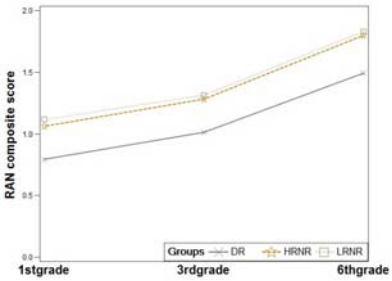
Rapid Automatized Naming (RAN)



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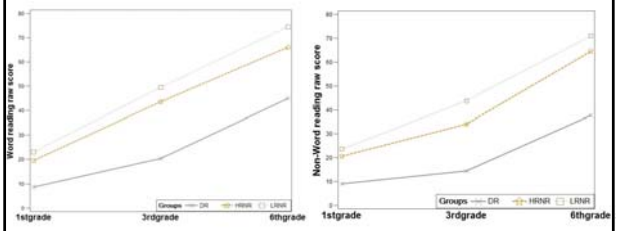
Reading



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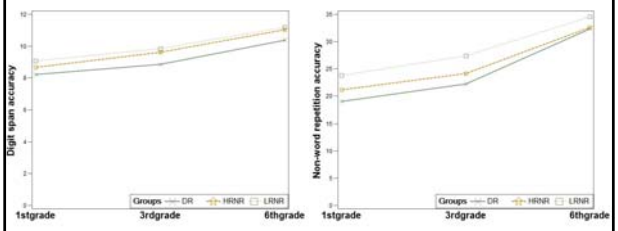
Verbal Short Term Memory (VSTM)



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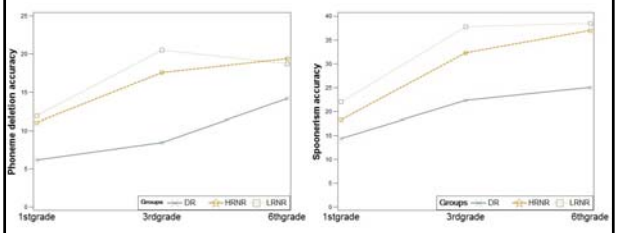
Phonological Awareness (PA)



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Phonology

- The DR group shows a broad (PA, RAN and VSTM) and enduring phonological deficit
  - The impairment in PA increases over time
- The NR-HR group shows a phonological deficit on those tasks that require the most fine-grained phonological representations (phoneme deletion, non-word repetition) until grade 3
  → family risk for dyslexia may be continuous
- PA is most strongly related to reading accuracy
  RAN is most strongly related to reading speed
- PA is the most important predictor in the early phase of learning to read
  RAN becomes a more prominent predictor for later reading development

Further details: Boets et al., 2010, Brit. J. Dev. Psych.
Dandache et al., 2014, Dyslexia

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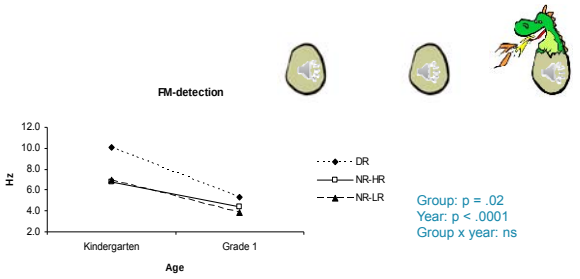
Auditory processing

- **FM detection** (changes of pitch over time)



Group: p = .02
Year: p < .0001
Group x year: ns

Further details: Boets et al., 2011, RIDD

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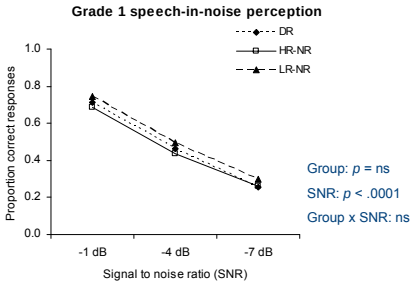
Speech-in-noise perception



Group: *p* = ns
SNR: *p* < .0001
Group x SNR: ns

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Speech perception

1. Speech-in-noise perception
   - Speech weighted Noise = 70 dB SPL
   - Presentation of 3 x 20 one-syllable words
   - Three SNR-levels
     - -1 dB SNR
     - -4 dB SNR
     - -7 dB SNR

2. Categorical perception
   - 10 step continuum /bak/ - /dak/
     (thanks to Van Beinum, van Leeuwen et al.)

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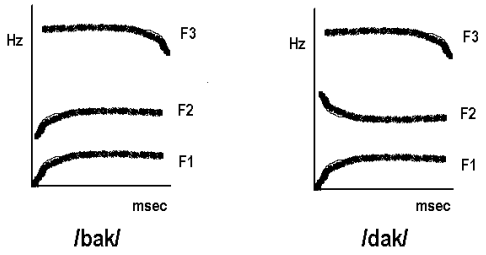
Categorical perception

- 10 step continuum ranging from /bAk/ to /dAk/



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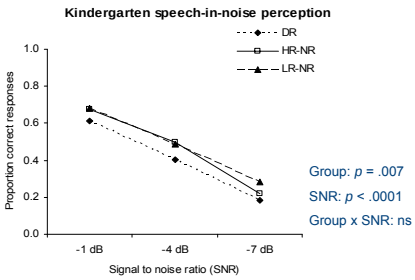
Speech-in-noise perception



Group: *p* = .007
SNR: *p* < .0001
Group x SNR: ns

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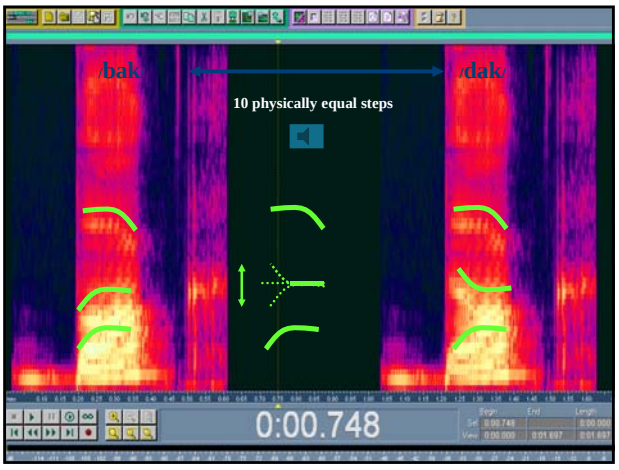
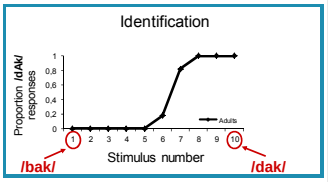


Categorical perception

Identification task

Normal readers:

- sudden transition in perception from /bak/ to /dak/
  = sharp phoneme boundary
  = consistent labeling



Persons with dyslexia:

- less steep slope
- less categorical
- more uncertainty

ba-da continuum: good speech temporal continuum

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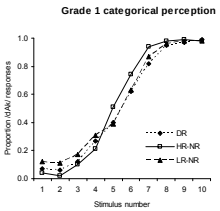
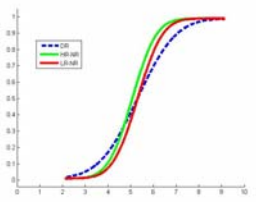
Categorical perception: grade 1

Raw data



Nonlinear fitting of slope



DR < NR-HR = NR-LR

*

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Integrated in a video game

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Conclusions categorical perception

- Evidence for a consistent deficit in categorical perception in the DR group
- This may indicate that their phoneme boundaries are less well specified

Further details: Boets et al., 2011, RIDD

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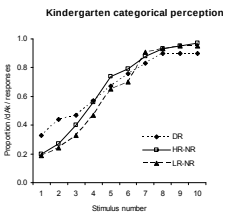
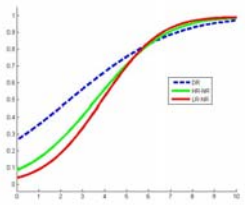
Categorical perception: kindergarten

Raw data



Nonlinear fitting of slope



DR < NR-HR < NR-LR

*

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Correlations between auditory processing, speech perception and phonology

- Cross-sectional correlations in kindergarten and in grade 1
  - between FM, speech-in-noise perception, categorical perception (slope), PA and reading
- Longitudinal/predictive correlations
  - between FM, speech-in-noise and categorical perception in kindergarten and PA in grade 1 and reading development
  - most predictive correlations disappear when taking into account autoregressive effects

Further details: Boets et al., 2011, RIDD

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General conclusions

- Both in preschool and in grade 1 DR children show a significant deficit in
  - low-level auditory processing
  - speech perception
  - phonology
- This implies that these deficits precede the literacy problem.
- Together with the significant predictive correlations, this may be suggestive of a causal relation between these skills.
- However, so far, we cannot demonstrate a robust directional relation between auditory processing, speech perception and phonology.

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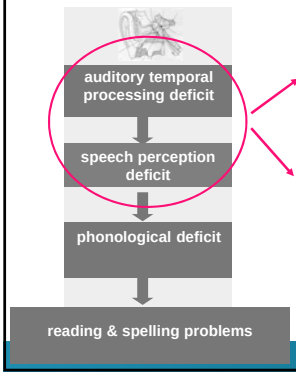
Exploring auditory processing
(PhD Maaike Vandermosten)



Specific speech processing deficit?

Specific temporal processing deficit?

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Temporal processing deficit theory

- Treatment consequences
  - Possibilities of early detection of children at risk
  - Keep in mind speech perception problems (especially in noisy environments)
  - Treatment possibilities are still controversial and not yet evidence based
    - e.g. Fast-For-Word program

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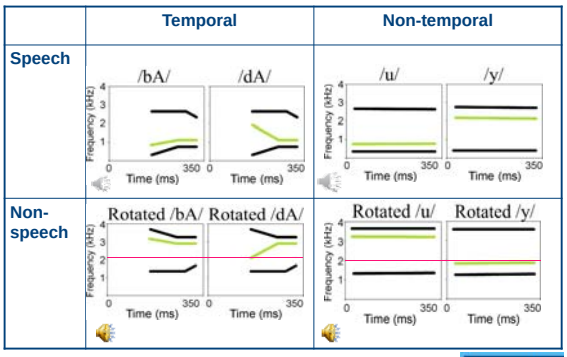
Categorical perception - factorial design



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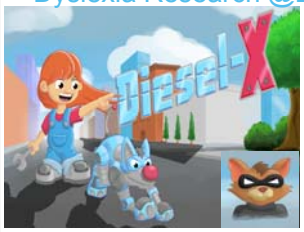
Dyslexia Research @Leuven: games4science



Screenshots of an intelligent game for psychophysics experiments with 5-year old children (FM-detection, rise time detection, letter knowledge)

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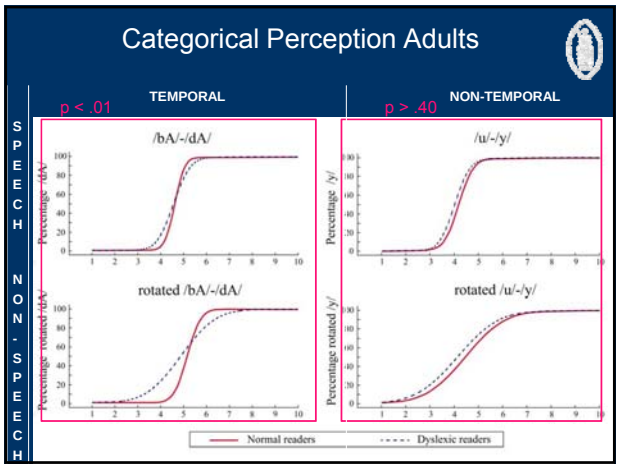
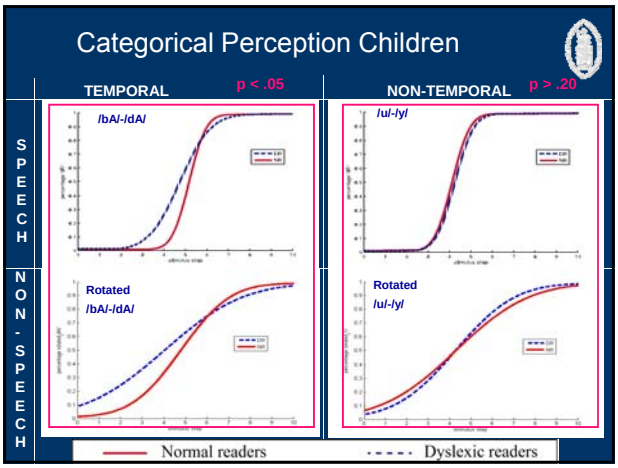
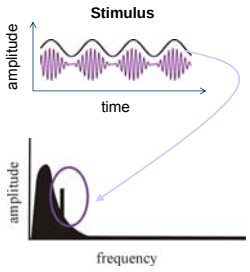
Categorical Perception Adults



Categorical Perception Children



Auditory steady-state responses



ASSR-TECHNIQUE

- ASSR is an evoked potential that is evoked in the brain as a response to a rhythmic auditory signal
- ASSRs: modulation processing
- EEG frequency spectrum: energy peak exactly at the frequency of the modulation

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Categorical Perception: Conclusions

- Problems are specific for rapidly changing sounds, but not specific for speech

  → Evidence for an auditory temporal processing deficit, not purely cognitive-linguistic

Further details: Vandermosten et al., 2010, *PNAS*
Vandermosten et al., 2011, *RIDD*

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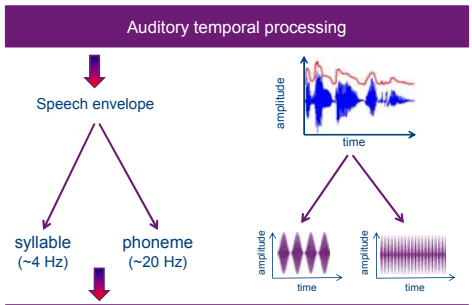
ASSR: model for speech



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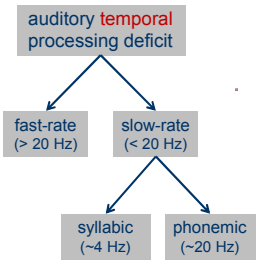
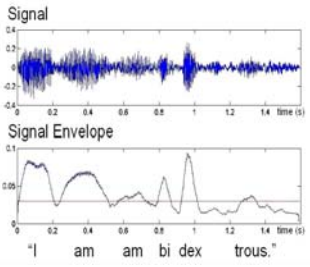
Neurophysiologic evidence via ASSR





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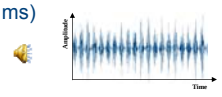
EEG: ASSR-measures

- Aim: Analyzing how sounds with the characteristics of syllable and phonemes are processed in the brain

Syllables
(250 ms)

Phonemes
(50 ms)



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ASSR-study in adults
(PhD Hanne Poelmans)

- Participants
  - university students
    - right handed and normal hearing at right ear
  - dyslexia (n=30):
    - formal diagnosis of dyslexia
    - word/non-word reading < 5th percentile
  - normal readers (n=30):
    - no history of reading problems
    - word/non-word reading > 5th percentile
- Multichannel ASSR *(Van Dun et al., 2009)*
  - 4 electrodes, referenced to Cz
  - 20 and 4 Hz 100% AM
    - Monaural right-ear presentation

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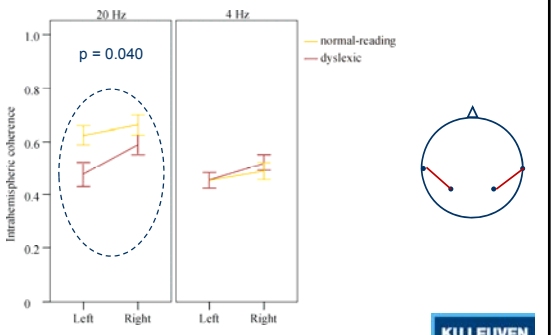
Results on intra-hemispheric coherence



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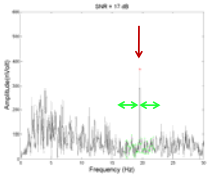
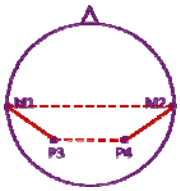
ASSR measures

signal-to-noise-ratio (SNR)



phase coherence
- functional connectivity between brain regions



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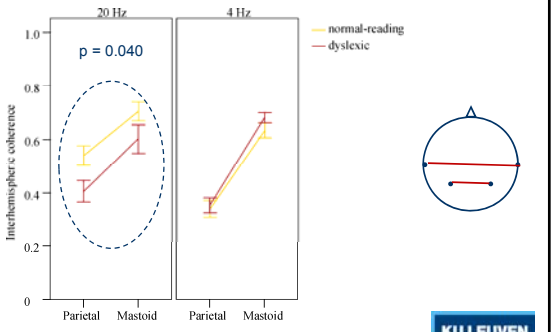
Results on inter-hemispheric coherence



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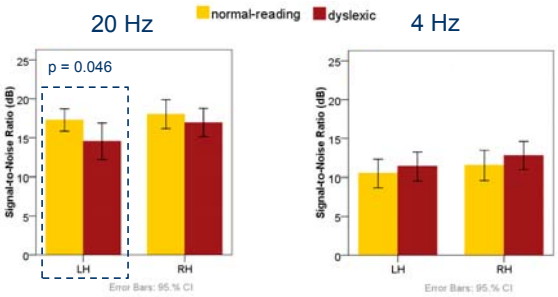
Results on SNRs

- Evidence for a neural phonemic-rate phase-locking deficit in dyslexia



ASSR study in adults: conclusions

- Findings in adults with dyslexia:

1. Normal syllabic-rate (4 Hz), but deviant phonemic-rate (20 Hz) processing
2. Phonemic-rate processing problem is reflected in:
   - Left hemispheric SNR
   - Intra-hemispheric coherence
   - Inter-hemispheric coherence

Further details: Poelmans et al., 2012, *Ear & Hearing*
Poelmans et al., 2011, *RIDD*

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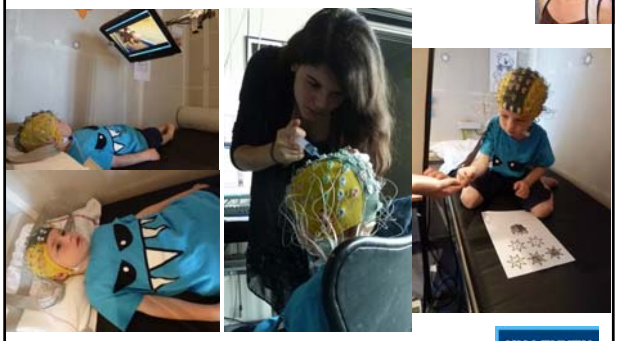
ASSR-study in kindergarten children
(PhD Sophie Vanvooren)



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PARTICIPANTS

	Dyslexic readers M (SD)	Normal readers M (SD)	Test statistics
N	20	20	
Subject characteristics			
Sex (male/female)	7/13	8/12	p = .75
Age (years)	22.1 (3.1)	21.4 (3.0)	p = .51
Non-verbal IQ (WAIS)	108 (10)	106 (10)	p = .59
Defining literacy measures			
Word reading	66.1 (1.9)	99.8 (11.4)	p < .0001
Pseudoword reading	66.0 (1.8)	107.9 (9.8)	p < .0001
Spelling	69.3 (6.5)	105.8 (9.6)	p < .0001
Reading underlying processes			
Phoneme awareness (effect size)	-2.79 (1.25)	0 (1)	p <.0001
Speech perception in noise (SRT in dB)	-8.2 (0.9)	-8.5 (1.1)	p = .30
Orthographic processing (raw score)	28.2 (3.6)	34.5 (2.6)	p <.0001

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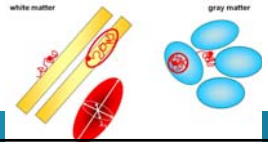
Neurophysiologic evidence via DTI
(PhD Maaike Vandermosten)

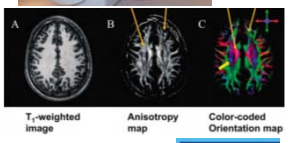
What is Diffusion Tensor Imaging?

- MRI-technique that gives an indication of the integrity of white matter

Why DTI study in dyslexia

- Auditory ***temporal*** processing deficit in dyslexia
  - ~ myelination / connectivity
- Exploring the neural reading network





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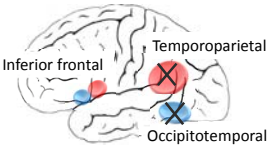
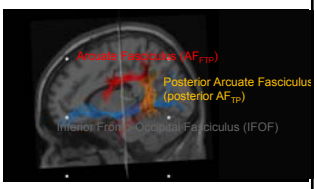
Structural reading network in adults with dyslexia

fMRI



DTI



+ right hemispheric tracts

= phonological aspects of reading

= Orthographic aspects of reading

= neural anomalies in dyslexics

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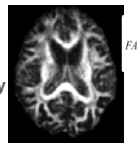
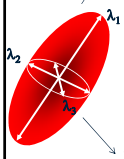
DTI measures

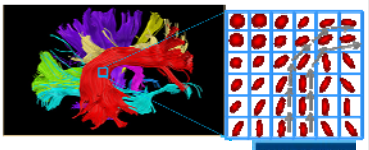
'summarize' tensor: fractional anisotropy



$$FA = \sqrt{\frac{3}{2}}\sqrt{\frac{(\lambda_1-\bar{\lambda})^2+(\lambda_2-\bar{\lambda})^2+(\lambda_3-\bar{\lambda})^2}{\lambda_1^2+\lambda_2^2+\lambda_3^2}}$$



fibertracking



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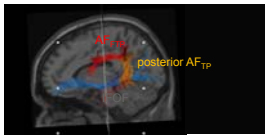
Structural reading network in adults with dyslexia

RESULTS: GROUP COMPARISON of FA
(controlled for IQ and quality index of DTI-acquisition)

	Normal Readers Mean FA (sd)	Dyslexic Readers Mean FA (sd)	P-value ANCOVA
Left AF_{FTP}	0.474 (0.017)	0.460 (0.025)	.029*
Left posterior AF_{TP}	0.455 (0.026)	0.444 (0.027)	.14
Left IFOF	0.485 (0.027)	0.486 (0.024)	.81



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Structural reading network in adults with dyslexia

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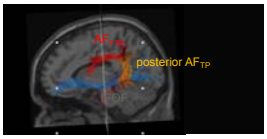
Left IFOF	0.485 (0.027)	0.486 (0.024)	.81
Right AF_{FTP}	0.422 (0.030)	0.426 (0.021)	.68



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Which network sustains reading at the very beginning?

- Brain not genetically pre-wired for reading!

Where is the primary deficit of dyslexia?

- White matter is plastic!

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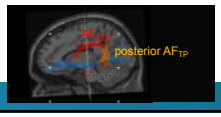
Structural reading network in adults with dyslexia

RESULTS: CORRELATIONS with FA
(controlled for literacy, IQ and quality index of DTI-acquisition)

	Phoneme awareness	Speech-in-noise perception	Orthography
Left AF_{FTP}	.31*	.23	-.05
Left posterior AF_{TP}	.21	.42**	.00
Left IFOF	.04	.18	.39*

No significant correlations
in right hemispheric tracts



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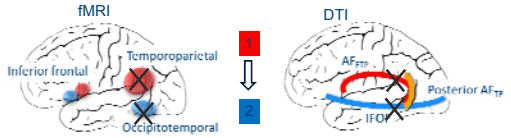
Structural reading network in at risk pre-readers

STANDARD NEUROANATOMICAL MODEL:

Predictions developmental sequence:



Predictions dyslexia:

- Primary deficit (phonological processing) → in left dorsal regions
- Secondary deficit (building up orthographic word representations) → in left ventral regions

Validation needed, especially on connections!

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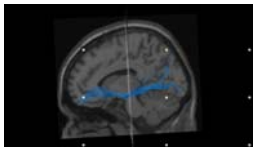
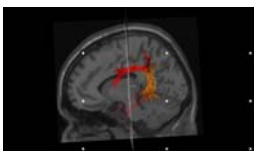
Structural reading network in adults with dyslexia

Left IFOF
- No group difference
- Corresponds to ventral orthographical route



Left AF
- Lower FA in dyslexic adults (direct AF_{FT})
- Corresponds to dorsal phonological route (direct AF_{FT} & posterior AF_{TP})



- No involvement of right hemispheric tracts

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Structural reading network in at risk pre-readers

- Participants
  - Last year of kindergarten
  - 45 family-risk for dyslexia pre-readers
    - at least one first-degree relative diagnosed as dyslexic
  - 45 no family risk for dyslexia pre-readers
  - Individual matching
    - Educational environment, i.e. same school!
    - Sex
    - Age
    - Non-verbal IQ (CPM)
    - Educational level of father and mother

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Structural reading network in at risk pre-readers

PARTICIPANTS	FRD+ (n = 36)	FRD- (n = 35)	Test statistics
Demographic data			
Gender (boy/girl)	23/13	18/17	Fisher's exact test: p = .34
SES	5.3 (1.6)	5.6 (1.6)	Fisher's exact test: p = .18
ADHD	2.5 (2.2)	1.5 (1.5)	Fisher's exact test: p = .40
Handedness (left/right)	5/30	2/32	Fisher's exact test: p = .43
Age in months	61.4 (3.1)	61.7 (3.0)	$F_{(1,27)} = 0.14$; p = .71
Non-verbal IQ	109.9 (13.2)	110.4 (10.0)	$F_{(1,27)} = 0.01$; p = .83
Cognitive predictors (composite score)			
Phonological Awareness	-0.06 (1.28)	0 (1)	$F_{(1,27)} = 0.20$; p = .66
Rapid Automatized Naming	-0.46 (1.08)	0 (1)	F $F_{(1,27)} = 3.41$; p = .09
Letter Knowledge	-0.51 (1.25)	0 (1)	$F_{(1,27)} = 9.75$; p = .02

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Structural reading network in at risk pre-readers

RESULTS: CORRELATIONS with FA

	LEFT			RIGHT		
	AF_{FTP}	Posterior AF_{TP}	IFOF	AF_{FTP}	Posterior AF_{TP}	IFOF
Phonological Awareness	0.30*	0.24 *	0.36**	0.27*	0.19	0.37**
Rapid Automatized Naming	0.13	0.07	0.20	0.16	-0.09	0.31**
Letter Knowledge	0.16	0.15	0.26 *	0.21	0.17	0.26 *

RESULTS: MULTIPLE REGRESSION

- phonological awareness was the only significant predictor of FA
  - no unique contribution of letter knowledge & rapid automatized naming

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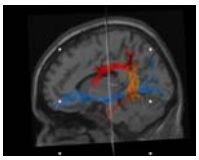
Structural reading network in at risk pre-readers



DTI to examine ventral and dorsal tracts on:

1. pre-reading anomalies related to family-risk factors of dyslexia
2. their specific cognitive function at that young age
   - correlation with phonological tasks (phonological awareness)
   - partial orthographic tasks (letter knowledge and rapid automatized naming)

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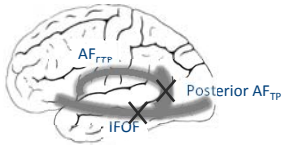
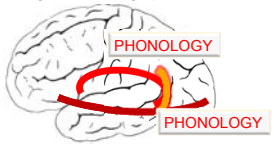
Structural reading network in at risk pre-readers

Group difference high vs low risk pre-readers?



Phonological vs Orthographic function?



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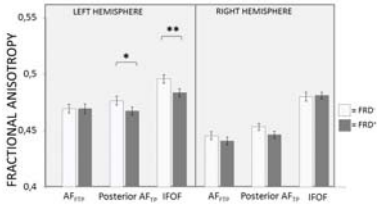
Structural reading network in at risk pre-readers

RESULTS: GROUP COMPARISON of FA

Group x Hemisphere x Tract interaction [$F_{(2,344)} = 3.17$, $p = .043$]



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Structural reading network in at risk pre-readers

Preliminary conclusions

- **White matter anomalies :**
  - predate reading → causal?
  - are located in left ventral and posterior dorsal connections
    → opposes the standard neuroanatomical model
- **White matter function:**
  - Phonological awareness is sustained bilaterally by both dorsal and ventral tract
    → gradual left lateralization and a gradual phonological versus orthographic specialization
- **Longitudinal follow-up needed**

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Thanks you for your attention!

DYSCO - Dyslexia research collaboration

- Parenting and Special Education (Psychology and Educational Sciences)
  - Prof. Pol Ghesquière, PhD
    - *(Bart Boets, PhD)*
    - Maaike Vandermosten, PhD
    - Anneli Veispak, PhD
    - *(Mieke Van Ingelghem)*
    - *(Sophie Dandache)*
    - Jeremy Law
    - Jolijn Vanderauwera
- Experimental ORL (Department of Neurosciences – Faculty of Medicine)
  - Prof. Jan Wouters, PhD
    - Heleen Luts, PhD
    - *(Hanne Poelmans, PhD)*
    - *(Ellen Vandewalle, PhD)*
    - Sophie Vanvooren
    - Astrid De Vos
- Radiology (University Hospital Leuven – Faculty of Medicine)
  - Prof. Stefan Sunaert, MD, PhD

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