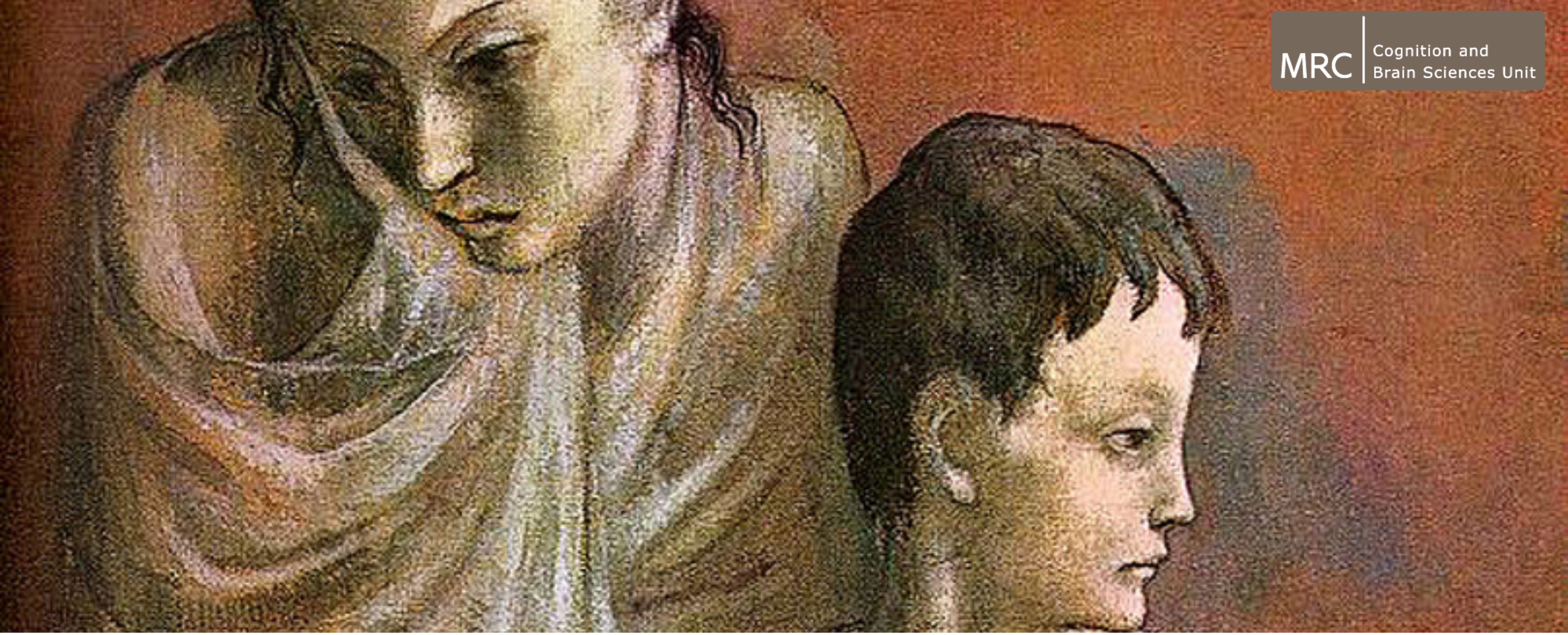

Developmental Cognitive Neuroscience

Joe Bathelt, PhD
MRC Cognition and Brain Sciences Unit
University of Cambridge
12th March 2018

Expected learning outcomes

- provide arguments for taking a developmental perspective in cognitive neuroscience
- describe general principles of macroscopic brain development
- interpret relationships between brain and cognition during development based on different theoretical approaches (maturational, skill learning, interactive specialisation)
- provide examples for different levels of observation and their interaction in developmental studies

Why study development?

Principles of brain development

Theories of neurocognitive development

Example

Why study development?

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Theories of neurocognitive development

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Why study development?

- complex cognitive skills in adults have **simpler precursors in development**
- studying development can provide insight into the **constituent processes** of cognition and inform theories of **cognitive architectures** across ages and ability levels

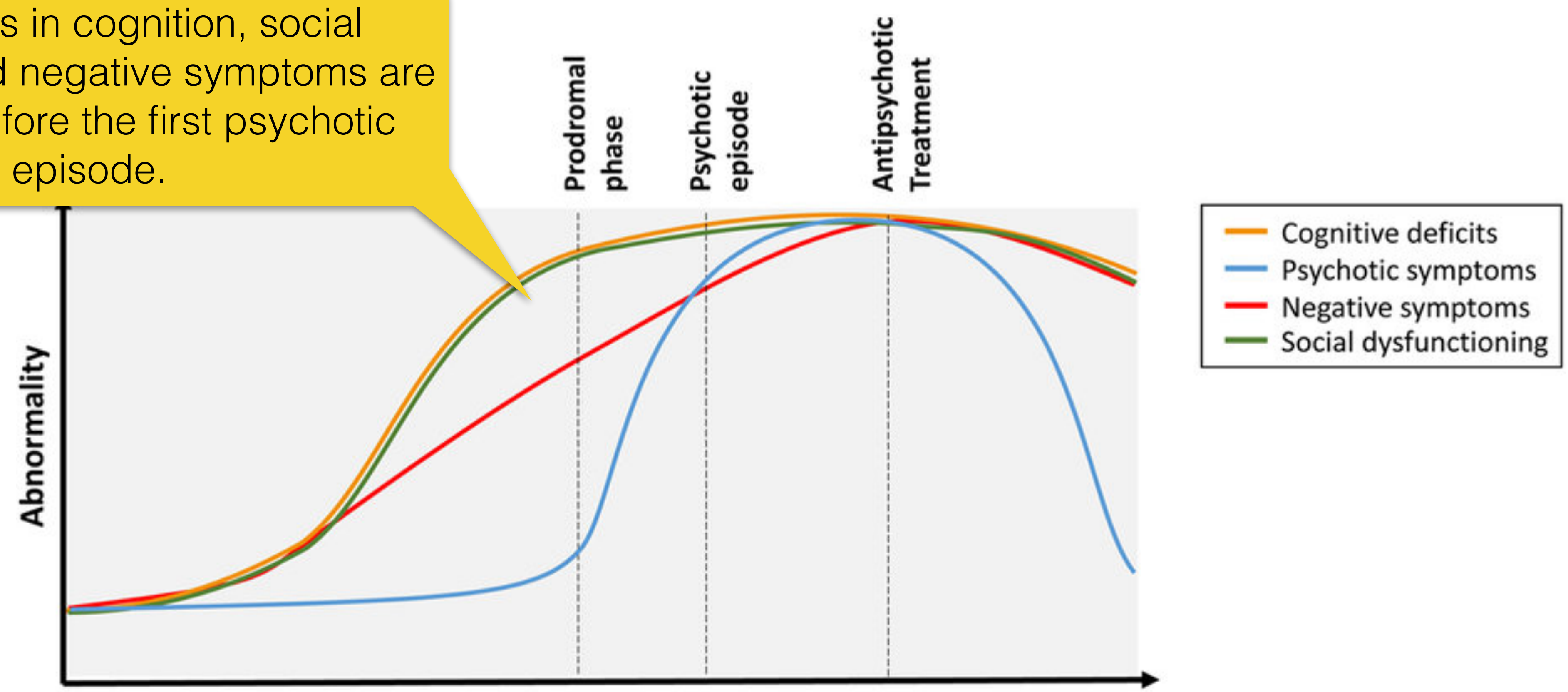
- executive functions in adults comprise many partially overlapping processes, including working memory, attention, inhibition, monitoring, planning, and problem solving
- research in infants and pre-schoolers suggest a precursor in the ability to overcome automatic processes, which then supports the development of other executive processes[1]
- illustration: https://youtu.be/0L7xzcvJzZc

The video shows the dimensional card sorting task (Diamond, 2001) with a pre-school age boy. He is aware of the rules, but does not sort the cards according to the correct dimension. This is thought to be related to immature inhibition of a prepotent response

- neurocognitive disorders typically **develop gradually**
- **precursors** or **prodromal stages** can be identified early in development
- identifying these early stages can help to **understand the mechanisms** of the disorder and can be used for **early targeted intervention** before symptoms become manifest

Example: schizophrenia

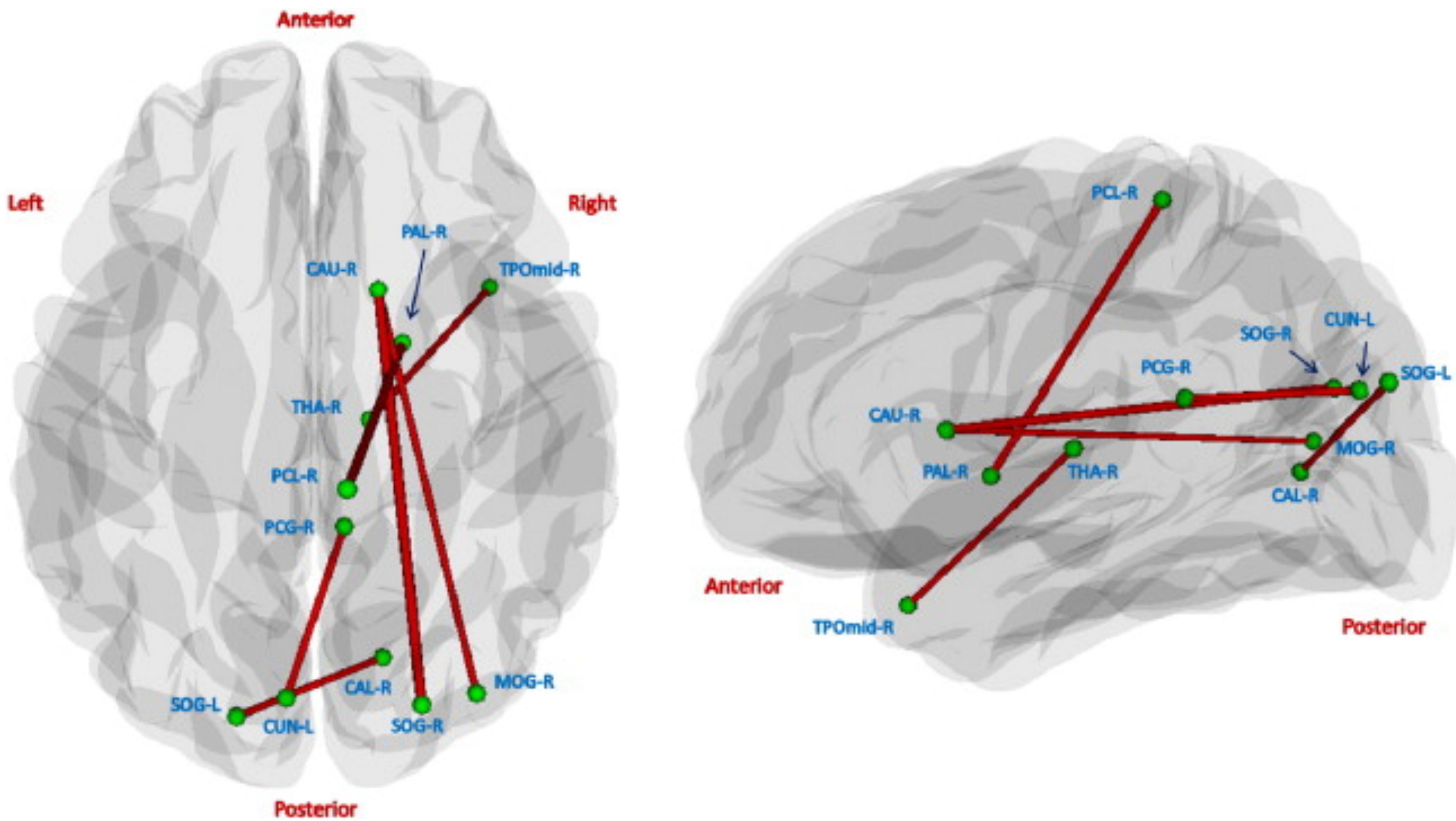
Differences in cognition, social behaviour, and negative symptoms are apparent before the first psychotic episode.



Sommer, I. E., Bearden, C. E., van Dellen, E., Breetvelt, E. J., Duijff, S. N., Maijer, K., et al. (2016). Early interventions in risk groups for schizophrenia: what are we waiting for? Npj Schizophrenia, 2, 16003. http://doi.org/10.1038/npjschz.2016.3

- there is a prodromal phase in schizophrenia, i.e. time before psychotic episodes emerge
- there are neural and cognitive differences during the prodromal period

Example: schizophrenia



Shi, F., Yap, P.-T., Gao, W., Lin, W., Gilmore, J. H., & Shen, D. (2012). Altered structural connectivity in neonates at genetic risk for schizophrenia: A combined study using morphological and white matter networks. NeuroImage, 62(3), 1622–1633. http://doi.org/10.1016/j.neuroimage.2012.05.026

neonates at high genetic risk for schizophrenia show reduced white matter connectivity for several cortical-subcortical connections

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Example: schizophrenia

- neonates at high genetic risk for schizophrenia show reduced white matter connectivity for several cortical-subcortical connections
- this might provide insight into disorder mechanisms
- however, the association are complex
- e.g. unaffected siblings have been found to show similar differences in structural network organisation[1]

Collin, G., Kahn, R. S., de Reus, M. A., Cahn, W., & van den Heuvel, M. P. (2014). Impaired Rich Club Connectivity in Unaffected Siblings of Schizophrenia Patients. Schizophrenia Bulletin, 40(2), 438–448. http://doi.org/10.1093/schbul/sbt162

Why study development?

Principles of brain development

Theories of neurocognitive development

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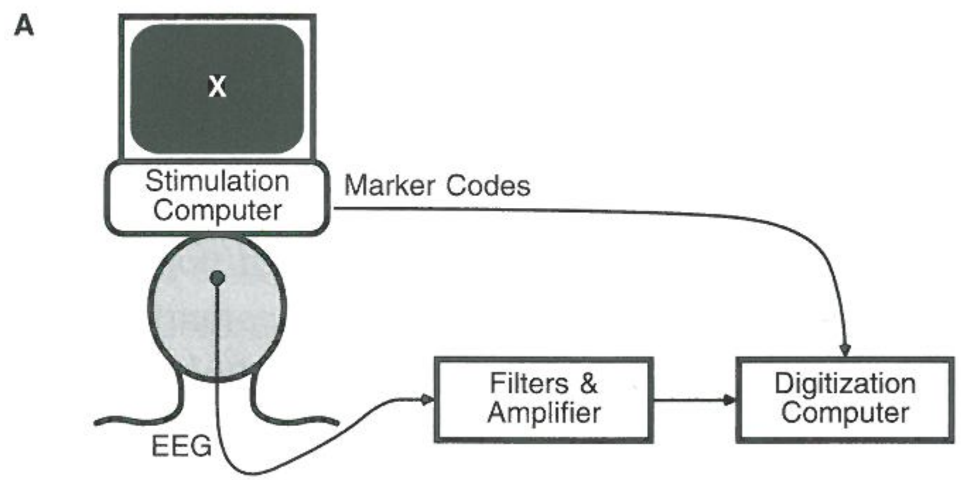
Principles of brain development

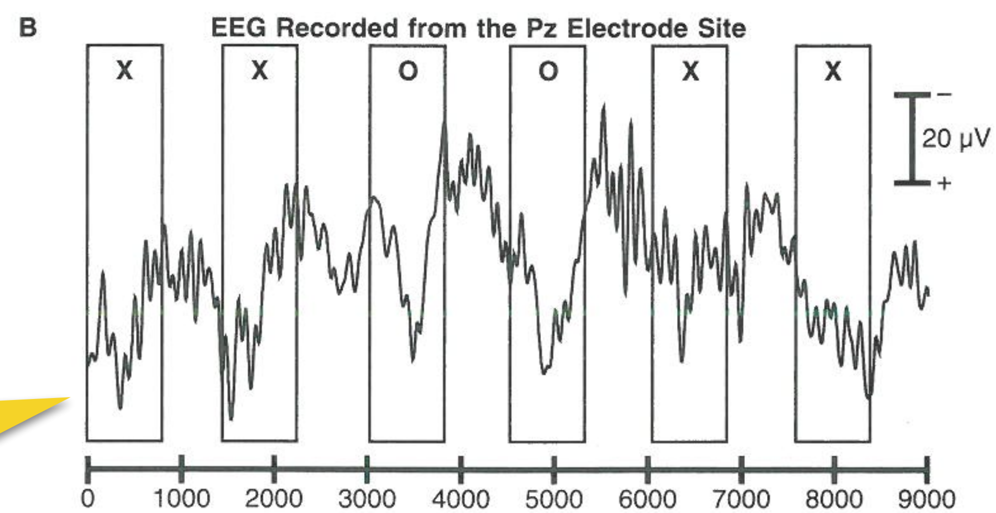
I. **Broadly tuned** to **specialised**
II. Different areas mature at a **different rates**
III. Network develops from **segregation** towards global **integration** between **specialised modules**

Quick aside: Event-related potentials (ERP)

Infant wearing a high-density EEG net while fixating a stimulus



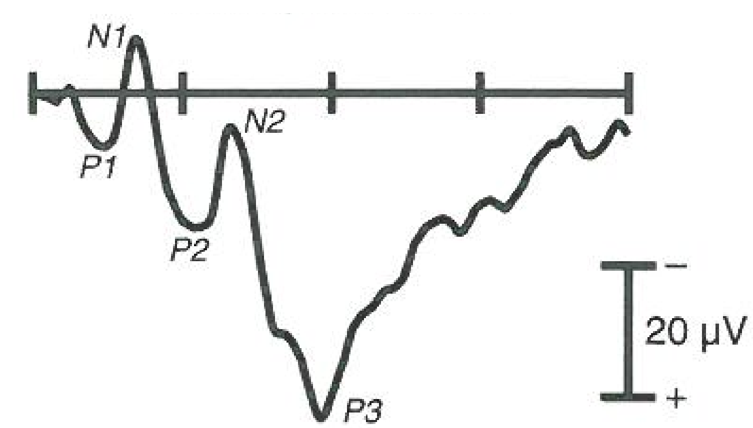
Averaging over all repetitions



the EEG is recorded over repeated presentations of the same stimulus / experimental condition

The event-related potential (ERP) is the averaged EEG over repeated presentations = time-locked average response. Different components can be distinguished that are named after their deflection (positive/negative) and their peak time/position in the sequence

Response averaged over all repetitions of the same stimulus

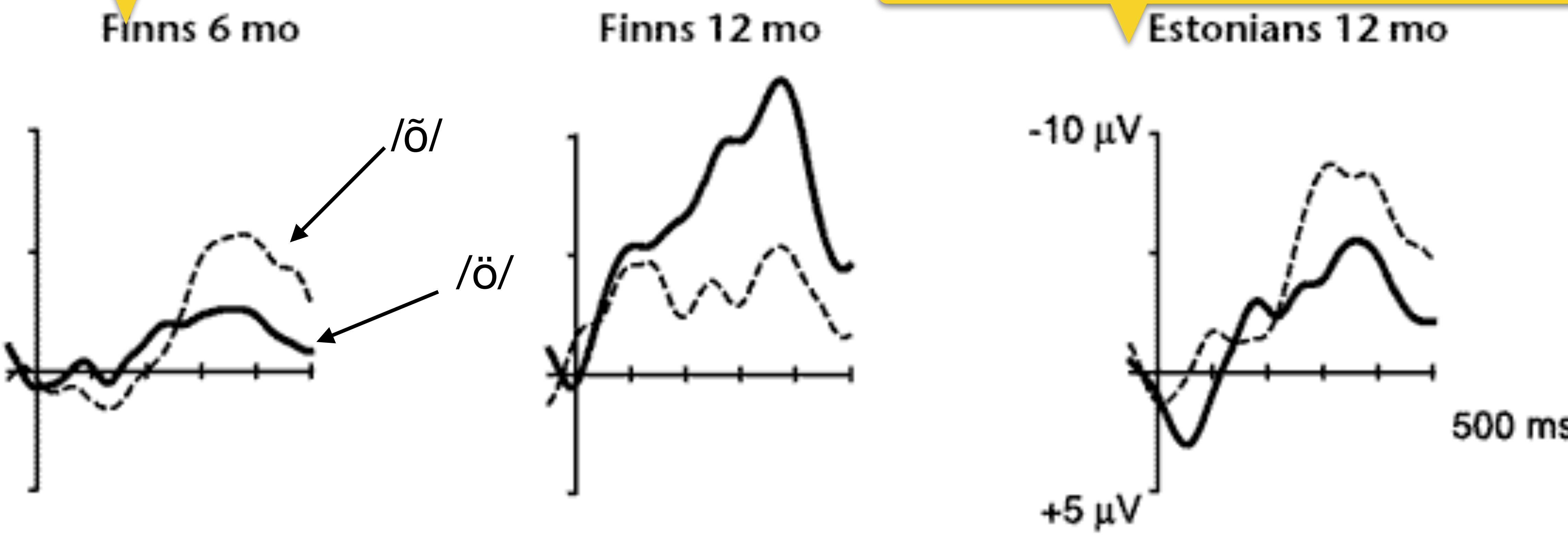


Luck, S. (2014). An Introduction to the Event-Related Potential Technique. Cambridge, MA: MIT Press

I. Broadly tuned to highly specialised

Infants distinguish between native (ö) and non-native (õ) speech sounds at 12 months, but not at 6 months

This is a control group here - both sounds exist in Estonian and they show a mismatch negativity response to both



→ differences between **native (ö) and non-native (õ) speech sounds** are detectable in the ERP signature at **12-months** of age, but not at **6 months** (perceptual narrowing)

Cheour, M., Ceponiene, R., Lehtokoski, A., Luuk, A., Allik, J., Alho, K., & Näätänen, R. (1998). Development of language-specific phoneme representations in the infant brain - Nature Neuroscience. Nature neuroscience, 1(5), 351–353. doi:10.1038/1561

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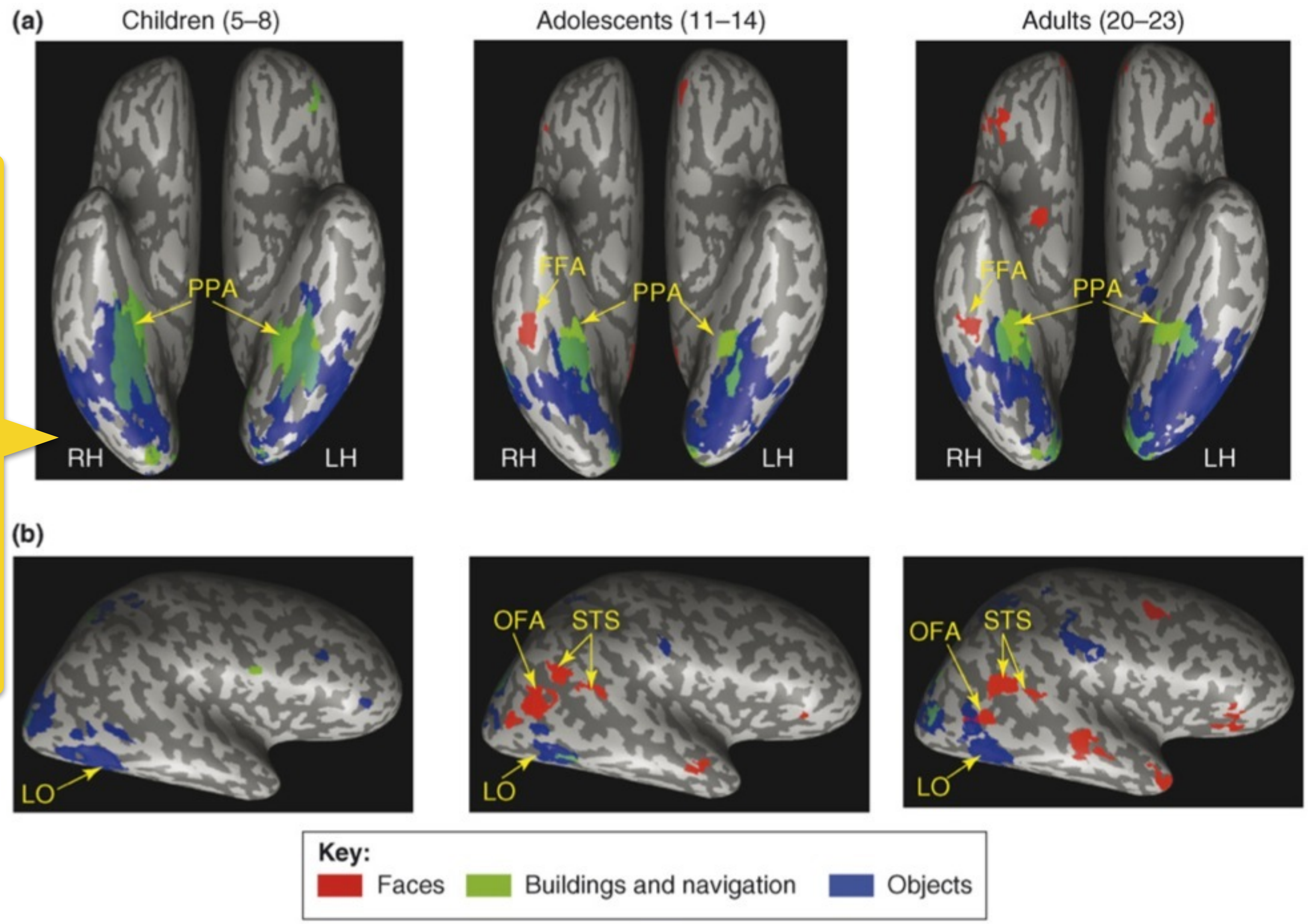
I. Broadly tuned to highly specialised



no face-selective contrast in youngest groups + large overlap of place and object contrast + larger area in the youngest age groups

- no face-selective activation in children, but in adolescents and adults

Scherf, K. S., Behrmann, M., Humphreys, K., & Luna, B. (2007). Visual category-selectivity for faces, places and objects emerges along different developmental trajectories. Developmental Science, 10, F15–30. doi:10.1111/j.1467-7687.2007.00595.x

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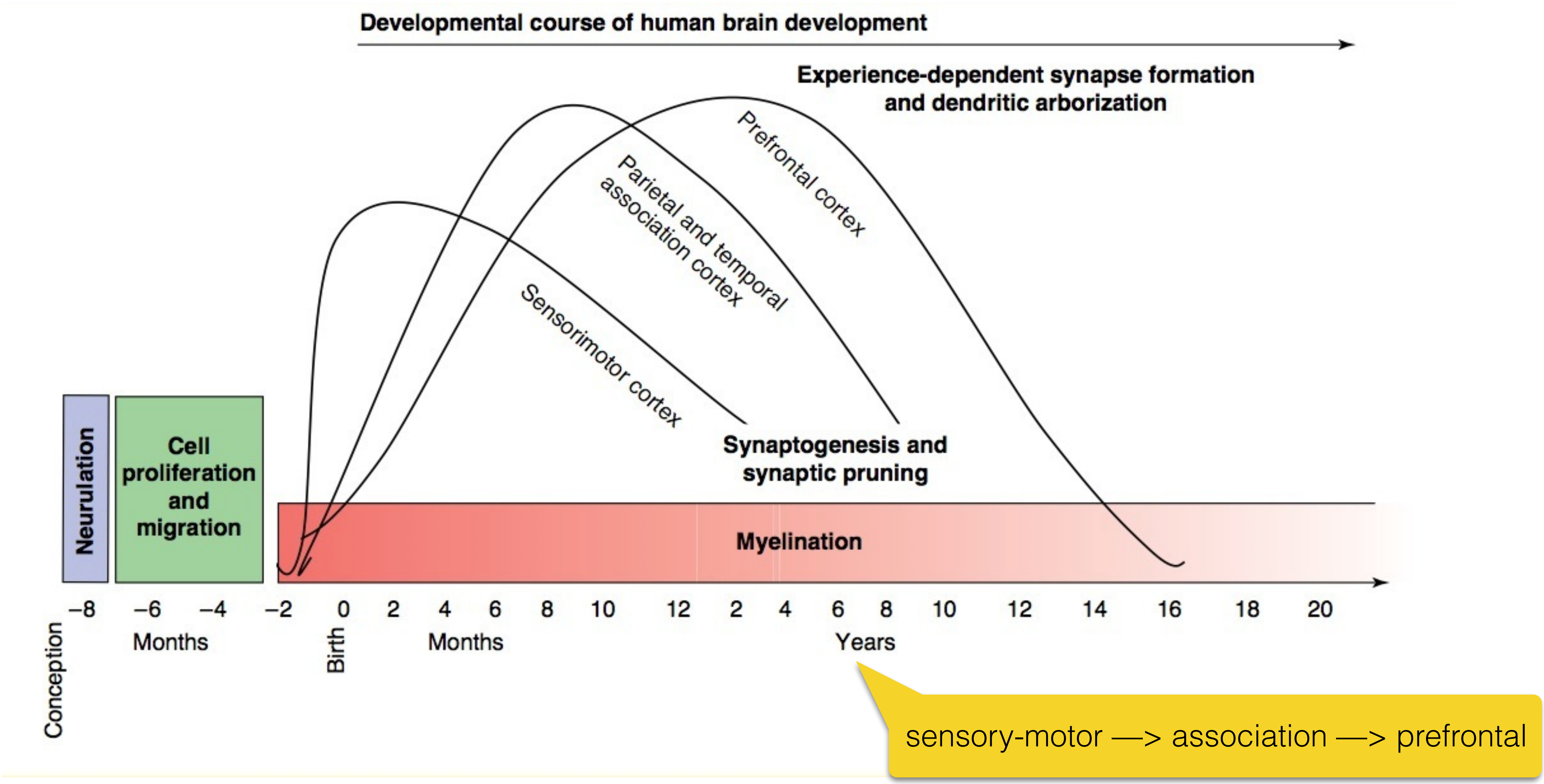
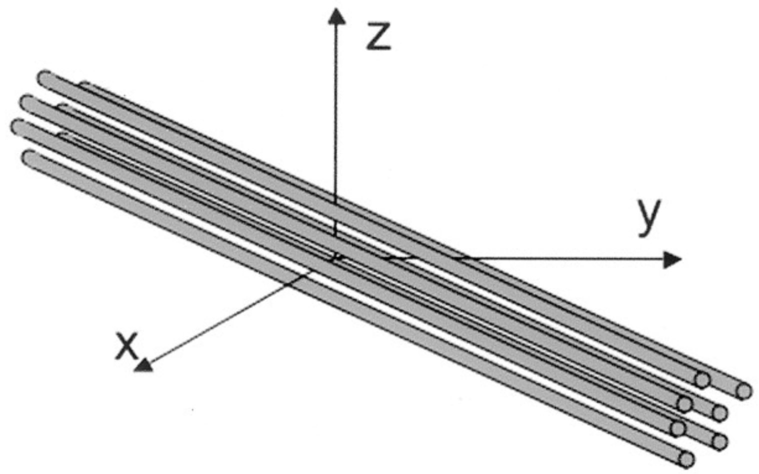
2. Different areas mature at different rates

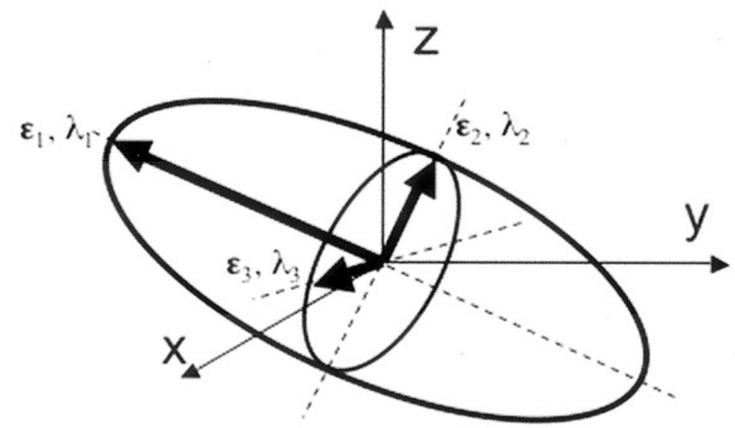


- general progression from posterior to anterior
- and from more ancient to more novel in terms of evolution

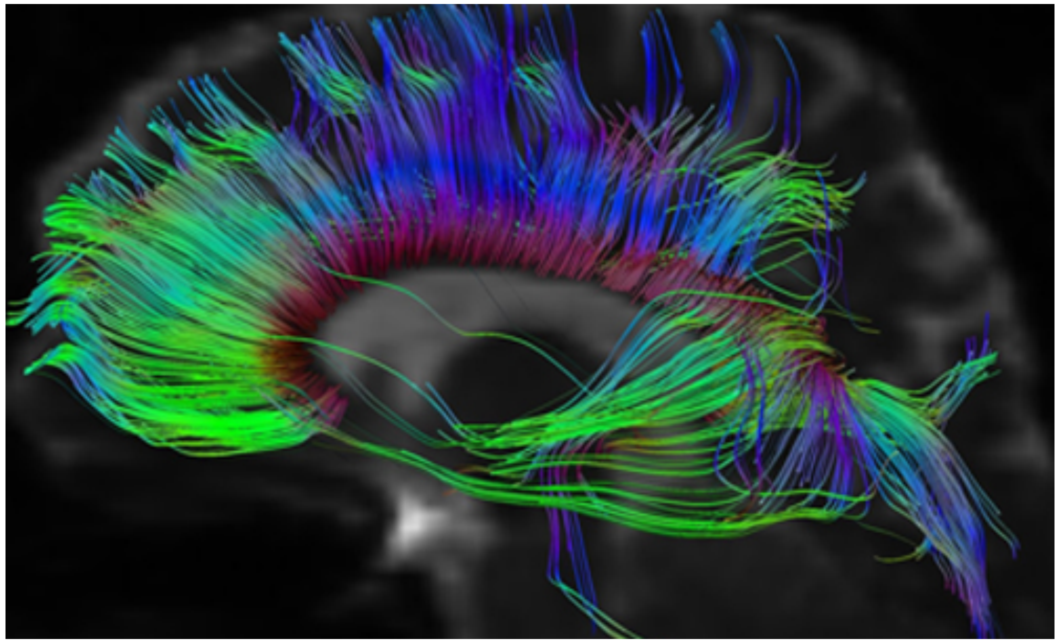
Casey, B. J., Tottenham, N., Liston, C., & Durston, S. (2005). Imaging the developing brain: what have we learned about cognitive development? Trends in Cognitive Sciences, 9(3), 104–110. doi:10.1016/j.tics.2005.01.011

Quick aside: Diffusion-weighted imaging





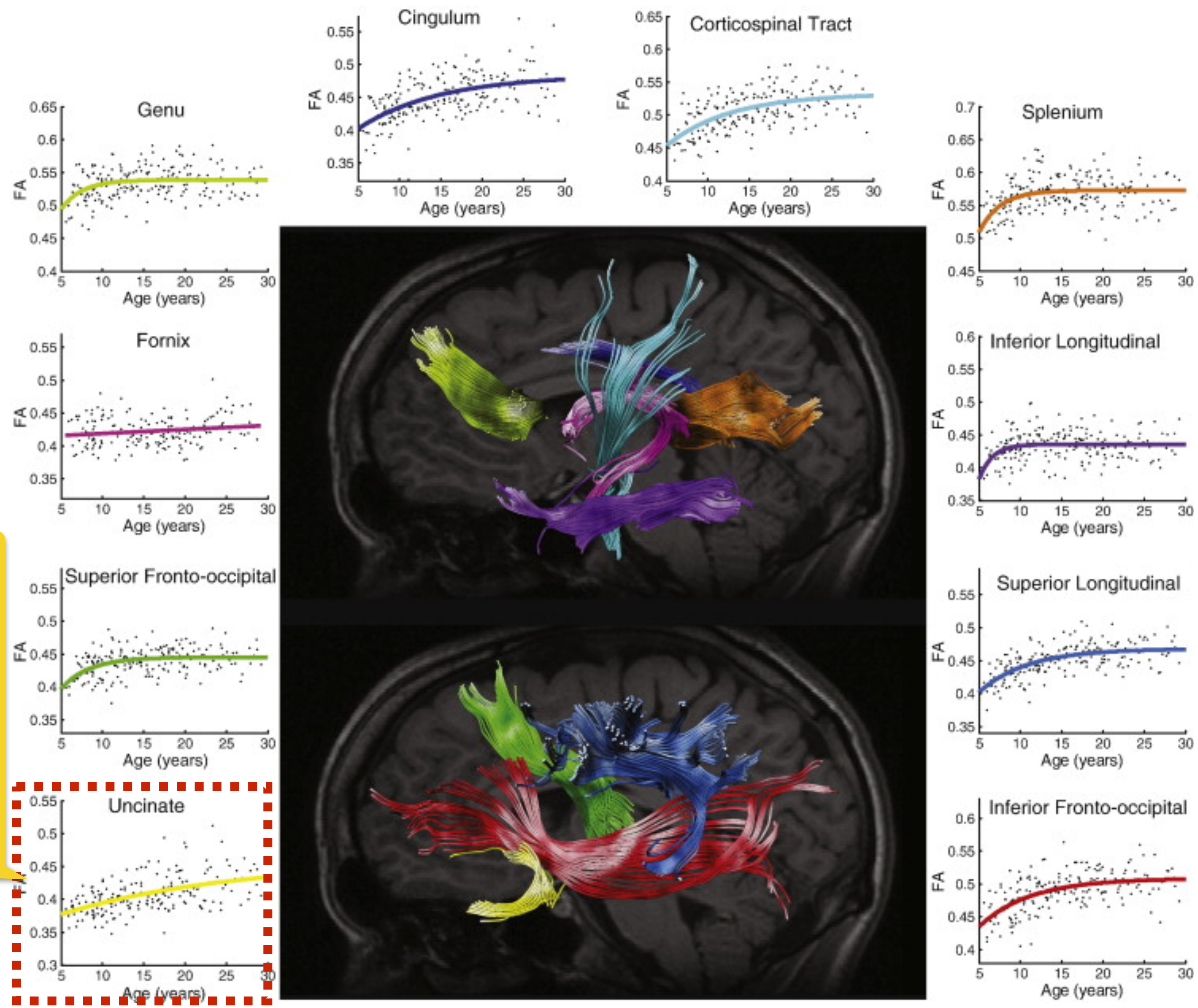
The diffusion of water is measured using specific MRI protocols. In highly organised tissues like white matter, diffusion is higher along the fibres than perpendicular to them.



We can use this information to reconstruct white matter structures and describe their tissue properties.

2. Different areas mature at different rates

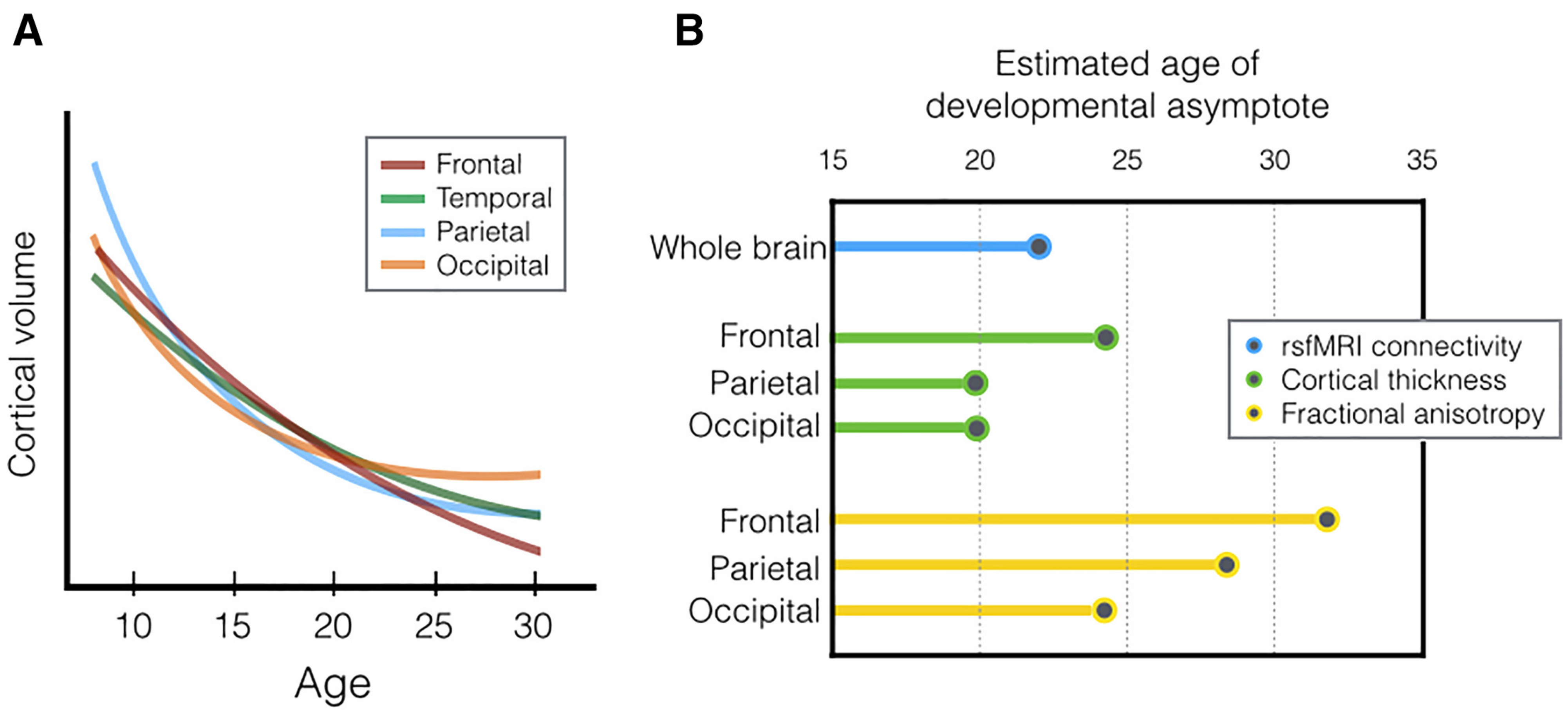
relatively early maturation in same tracts — reach plateau earlier



prolonged maturation in other areas, e.g. uncinate fasciculus - connected temporal and frontal lobe

Lebel, C., Walker, L., Leemans, A., Phillips, L., & Beaulieu, C. (2008). Microstructural maturation of the human brain from childhood to adulthood. NeuroImage, 40(3), 1044–1055. http://doi.org/10.1016/j.neuroimage.2007.12.053

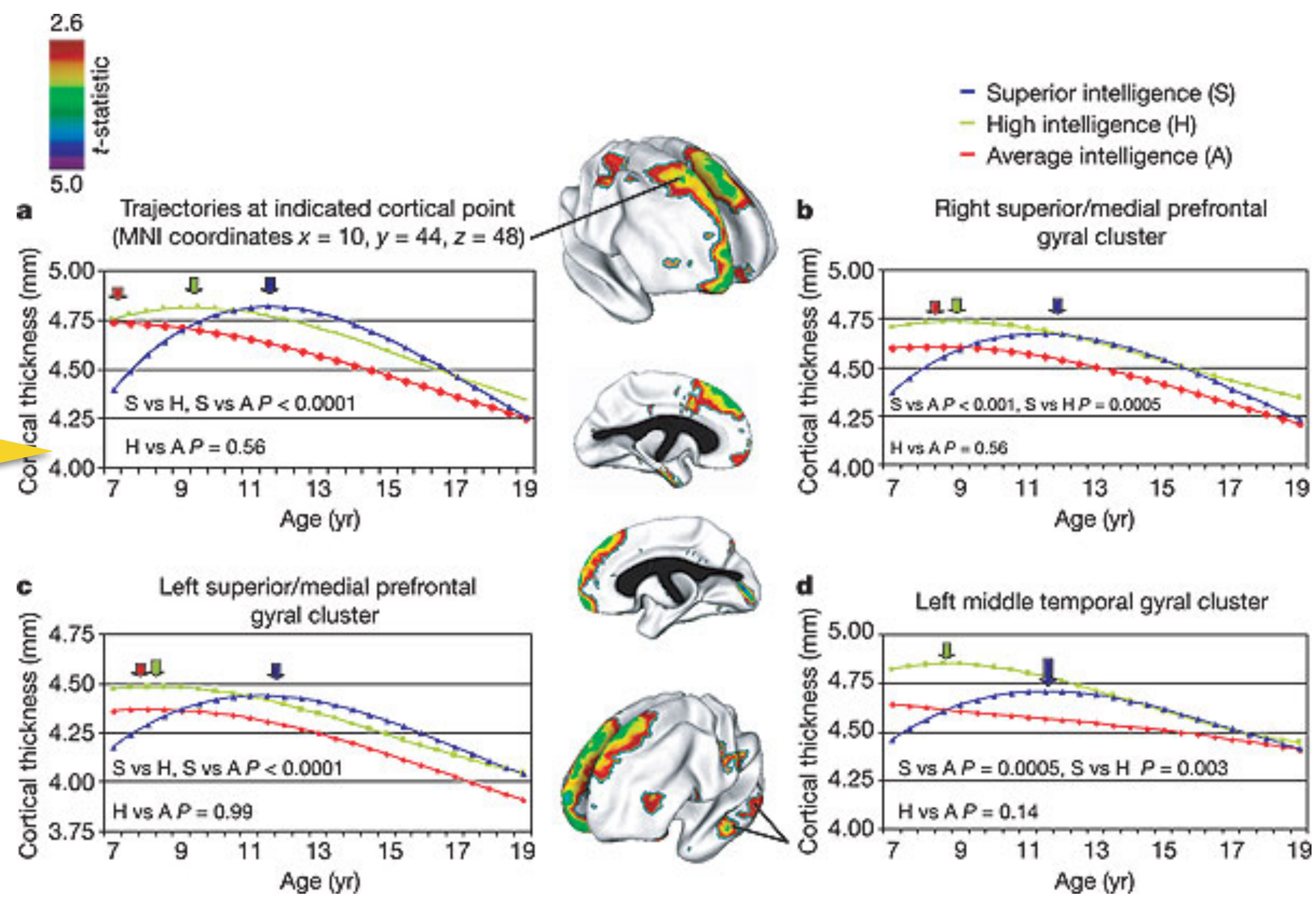
2. Different areas mature at different rates



- overview of expected maturation of different aspects of brain morphology

Somerville, L. H. (2016). Searching for Signatures of Brain Maturity: What Are We Searching For? Neuron, 92(6), 1164–1167. http://doi.org/10.1016/j.neuron.2016.10.059

2. Different areas mature at different rates

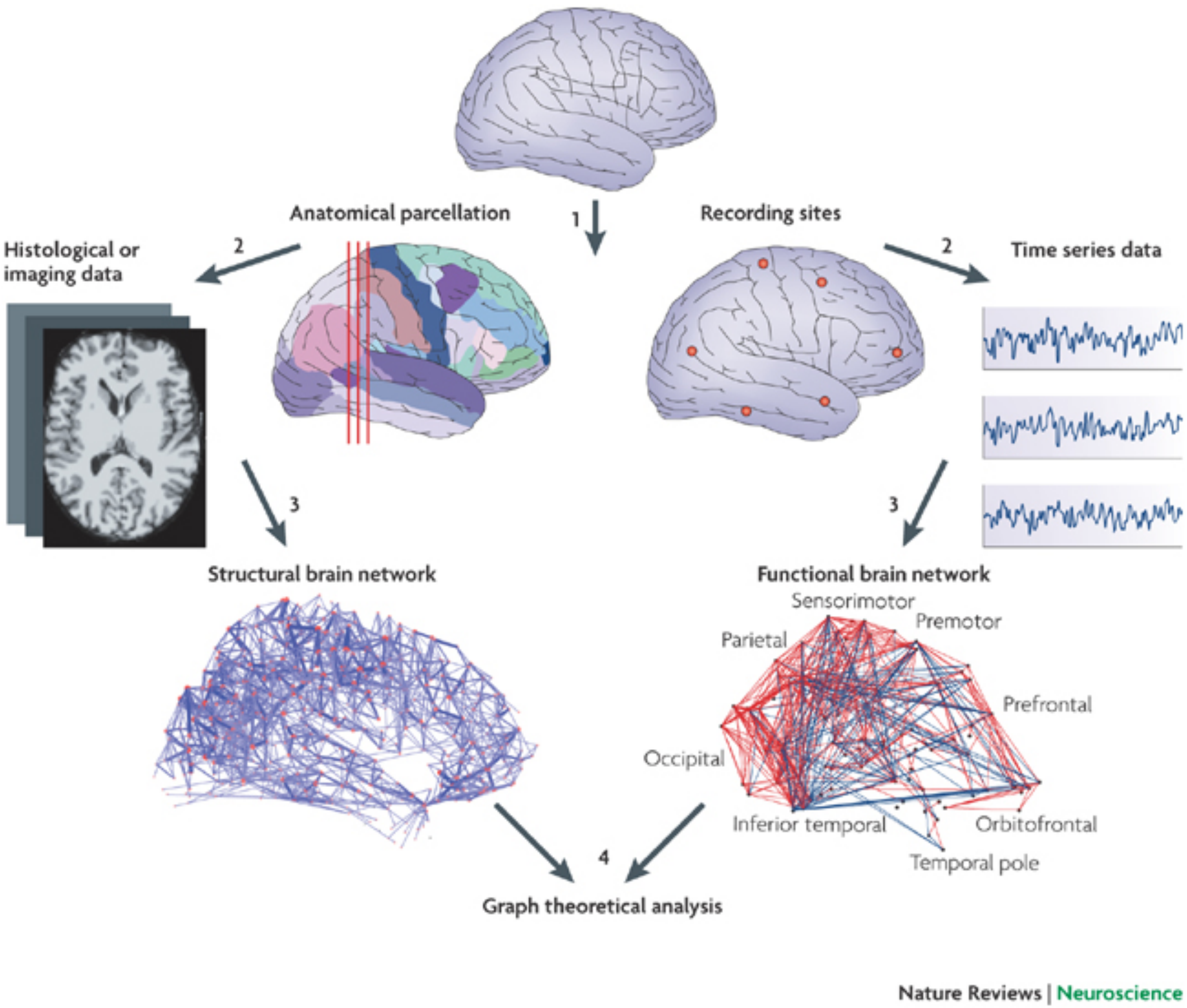


the time course of cortical maturation may be more important than a static measures at one time point

- example of how the trajectory of brain morphology development may relates to cognitive performance

Shaw, P., Greenstein, D., Lerch, J., Clasen, L., Lenroot, R., Gogtay, N., et al. (2006). Intellectual ability and cortical development in children and adolescents. Nature, 440(7084), 676–679. http://doi.org/10.1038/nature04513

Quick aside: network neuroscience

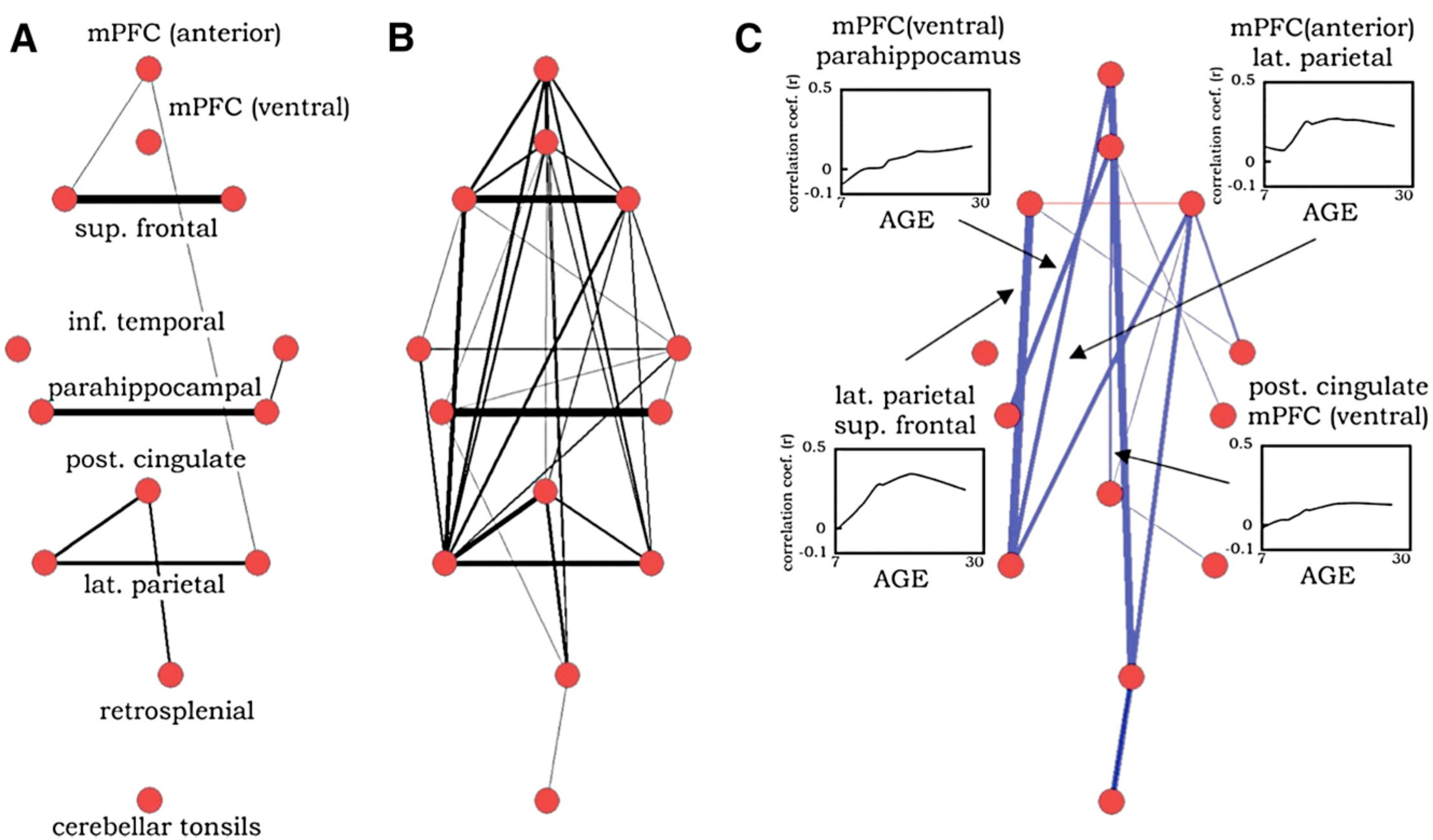


- the brain can be described as a network of:
  - **brain regions (nodes)**
  - **statistical relationships** between signals or **structural connections** (**edges**)
- **network science** methods can be applied to describe and study properties of brain networks

Bullmore, E., & Sporns, O. (2009). Complex brain networks: graph theoretical analysis of structural and functional systems. Nature Reviews Neuroscience, 10(3), 186–198. http://doi.org/10.1038/nrn2575

3. Development of Brain Networks

7-9 years | 21-31 years | Difference Map



- tendency towards higher anterior-posterior integration[1]
- however: in scanner motion may play a role[2]

1. Fair, D. A., Cohen, A. L., Dosenbach, N. U. F., Church, J. A., Miezin, F. M., Barch, D. M., et al. (2008). The maturing architecture of the brain's default network. Proceedings of the National Academy of Sciences of the United States of America, 105(10), 4028. http://doi.org/10.1073/pnas.0800376105
2. Satterthwaite, T. D., Wolf, D. H., Loughead, J., Ruparel, K., Elliott, M. A., Hakonarson, H., et al. (2012). Impact of in-scanner head motion on multiple measures of functional connectivity: Relevance for studies of neurodevelopment in youth. NeuroImage, 60(1), 623–632. http://doi.org/10.1016/j.neuroimage.2011.12.063

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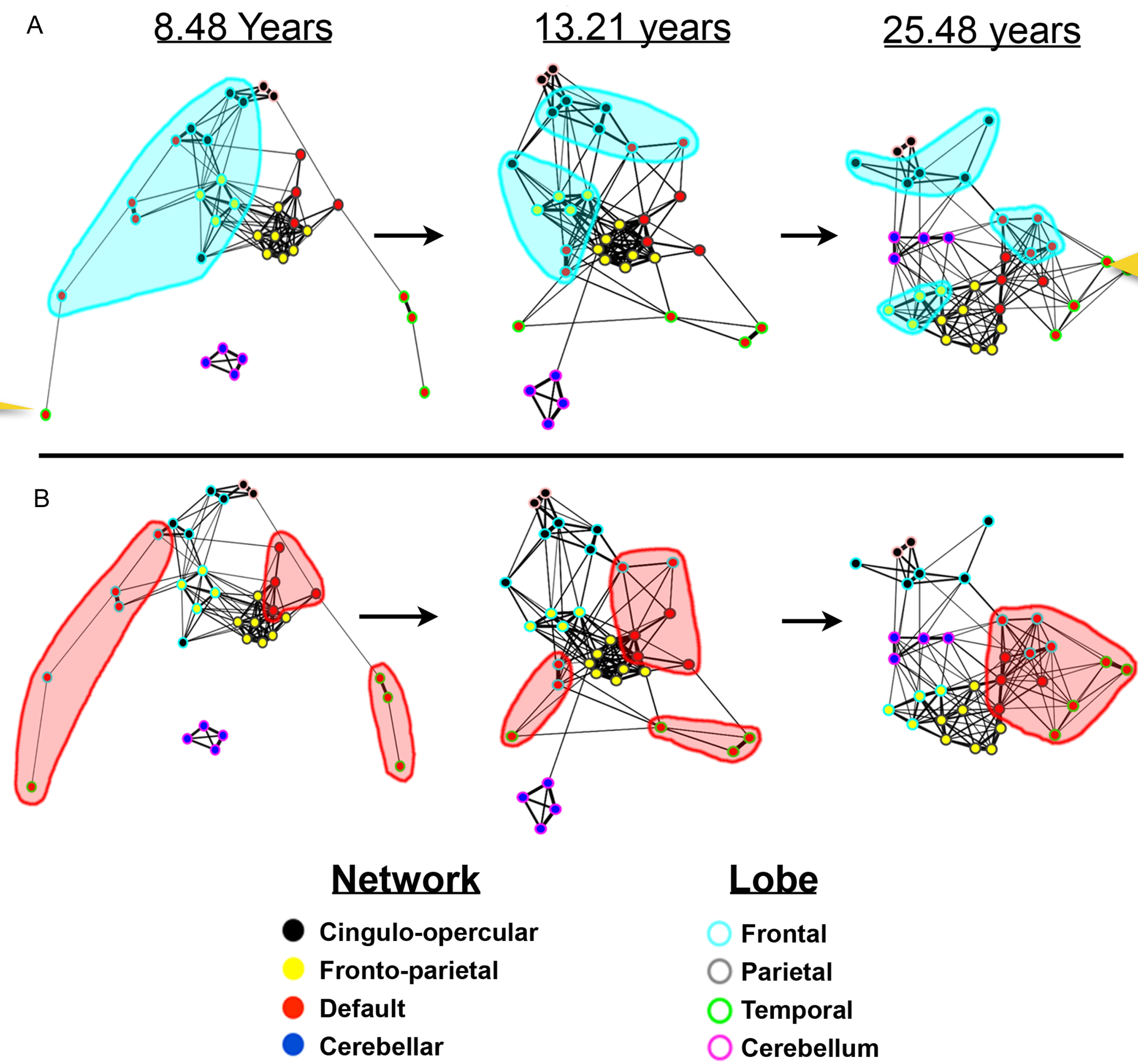
3. Development of Brain Networks

Many nodes are not well integrated earlier in development



In the adult, nodes are more close integrated and form communities of nodes involved in similar processes

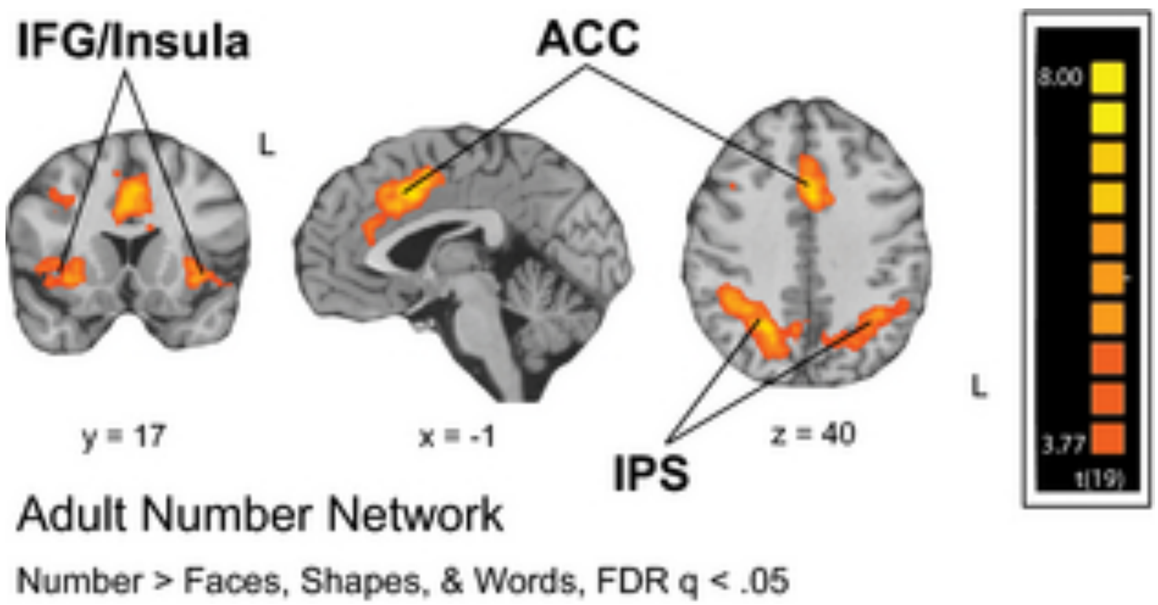
- Network develops from **segregation** towards global **integration** between **specialised modules**

Fair, D. A., Cohen, A. L., Power, J. D., Dosenbach, N. U. F., Church, J. A., Miezin, F. M., et al. (2009). Functional Brain Networks Develop from a “Local to Distributed” Organization. PLoS Computational Biology, 5(5), e1000381. http://doi.org/10.1371/journal.pcbi.1000381

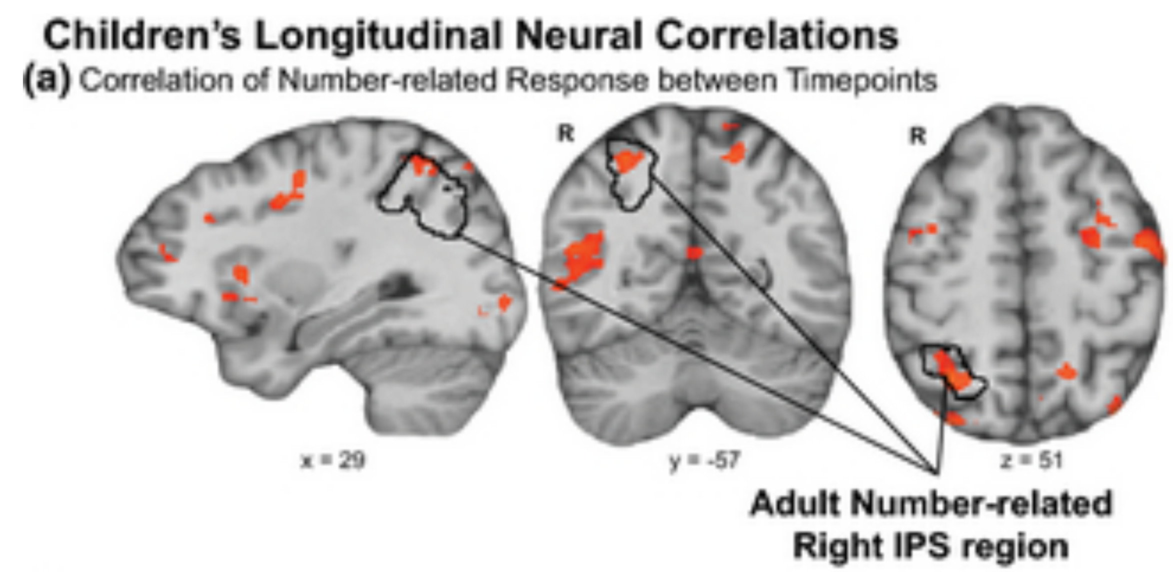
Exercise

- suppose you were interested in how the **neural correlates of number processing** change over development
- you ran an **fMRI study** comparing **adults and children** on a numerical processing task
- what **differences and similarities** would you expect in **task-specific activations** between children and adults?

Exercise



network of regions related to numerosity processing in adults



children's longitudinal changes of number-related processing implicate the same core network of regions indicated in adults, but also regions outside of the network in the frontal and prefrontal cortex

Emerson, R. W., & Cantlon, J. F. (2015). Continuity and change in children's longitudinal neural responses to numbers. Developmental Science, 18(2), 314–326. http://doi.org/10.1111/desc.12215

Why study development?

Principles of brain development

Theories of neurocognitive development

Example

Theories of neurocognitive development

I. Maturational
II. Skill Learning
III. Interactive Specialisation

Maturational View

- different brain regions **mature at different rates**
- **maturation** coincides with the **emergence of new abilities**
- development is like **inverse neuropsychology** regions come ‘on line’ rather than being damaged

Maturational View

- example:
  - **risk taking** and preference for **immediate gratification** in **teenagers** is often seen as being related to the **late maturation of the prefrontal cortex**

https://www.nimh.nih.gov/health/publications/the-teen-brain-still-under-construction/index.shtml

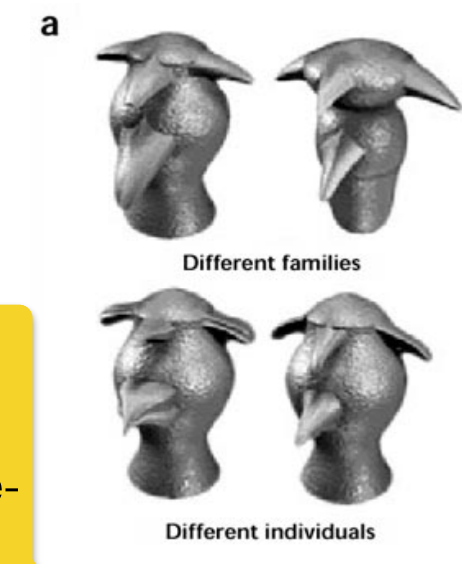
for example see: Powell, K. (2006). Neurodevelopment: How does the teenage brain work? Nature, 442(7105), 865–867. http://doi.org/10.1038/442865a

Skill Learning View

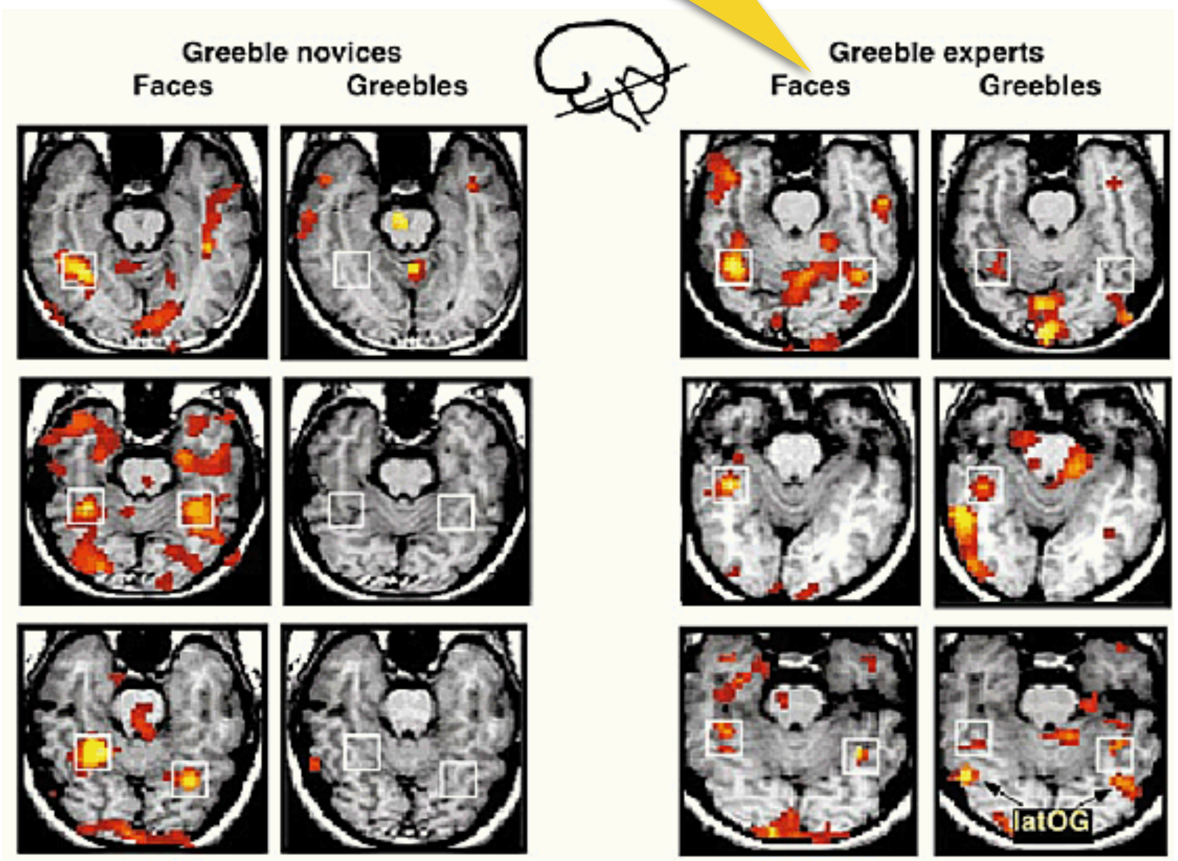
- changes in cognitive abilities and neural correlates are related to exposure to learning opportunities
- commonalities in development are ascribed to similar exposure across development, e.g. identifying faces, canonical learning in school etc.

Skill Learning View

- example:
  - over development presentation of face stimuli is associated with a specific activation in an area of the fusiform gyrus (fusiform face area)
  - when training to categories artificial complex stimuli (Greebles) activation is similar to the face activation
  - specialisation of the FFA might therefore be experience driven



The group trained in Greeble discrimination shows activation in a ”face-specific” area

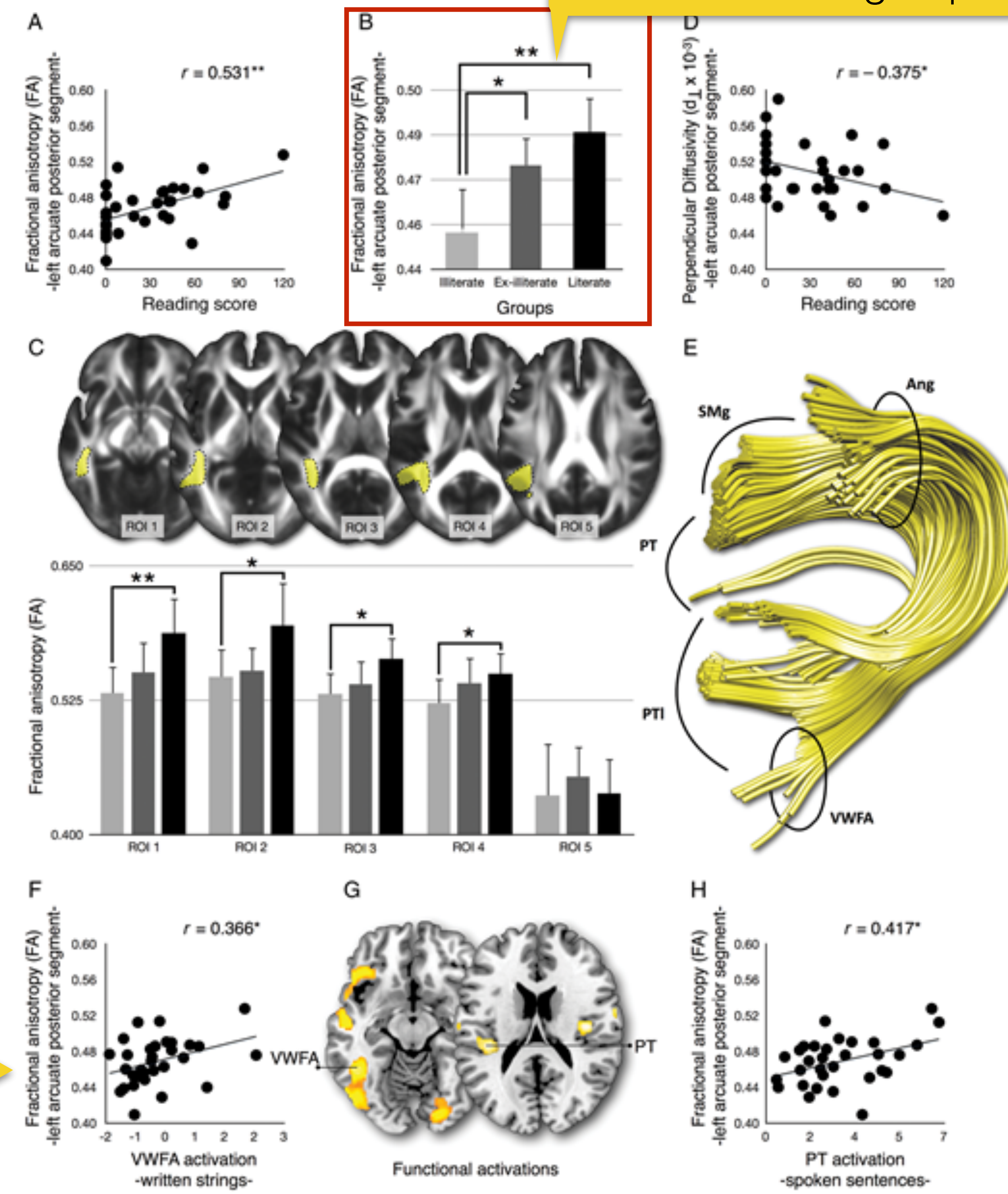


Gauthier, I., Tarr, M. J., Anderson, A. W., Skudlarski, P., & Gore, J. C. (1999). Activation of the middle fusiform “face area” increases with expertise in recognizing novel objects - Nature Neuroscience. Nature Neuroscience, 2(6), 568–573. http://doi.org/10.1038/9224

Skill Learning View

The literate and ex-illiterate group show high FA in the arcuate fasciculus. FA in this tract is sign. lower in the illiterate groups

- example:
  - learning to read is associated with changes in left white matter tracts related to language processing
  - these changes are similar in early and late literates



FA in the arcuate fasciculus also relates to the strength of the BOLD signal in the visual word form area (VWFA) activation

Thiebaut de Schotten, M., Cohen, L., Amemiya, E., Braga, L. W., & Dehaene, S. (2014). Learning to Read Improves the Structure of the Arcuate Fasciculus. Cerebral Cortex, 24(4), 989–995. http://doi.org/10.1093/cercor/bhs383

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Interactive Specialisation View

- cognitive functions are **emergent properties of interactions between brain regions**
- this is in contrast to the modular view assumed in the maturational account

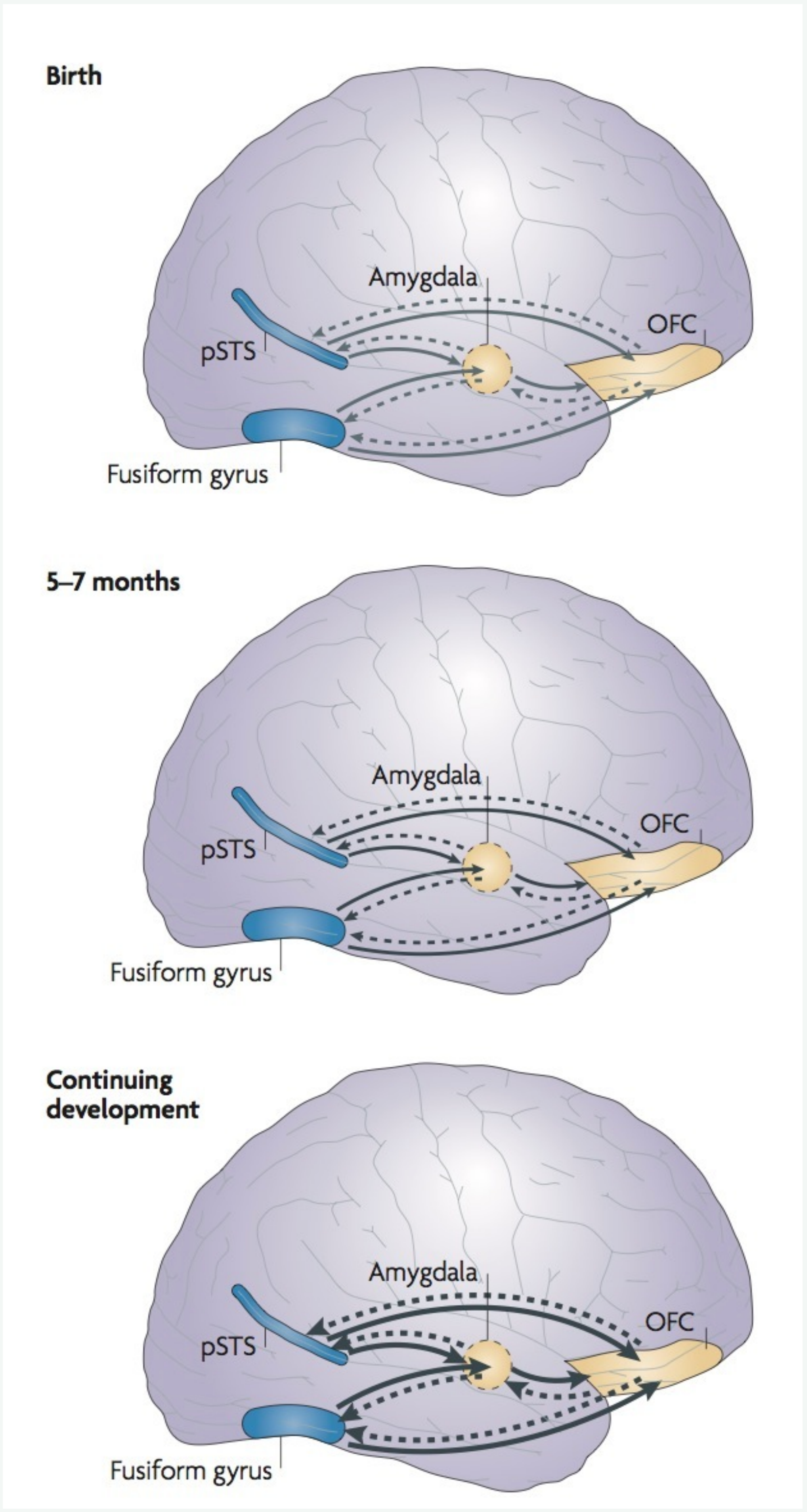
Interactive specialisation areas involved in processing of emotional facial expressions

I. Anatomical emergence

II. Experience-expectant functional development

III. Experience-dependent functional development

The examples in the last part of the talk illustrate this in more detail



Leppänen, J. M., & Nelson, C. A. (2009). Tuning the developing brain to social signals of emotions. Ten years of Nature Reviews Neuroscience: insights from the highly cited, 10, 37–47. doi:10.1038/nrn2554

Why study development?

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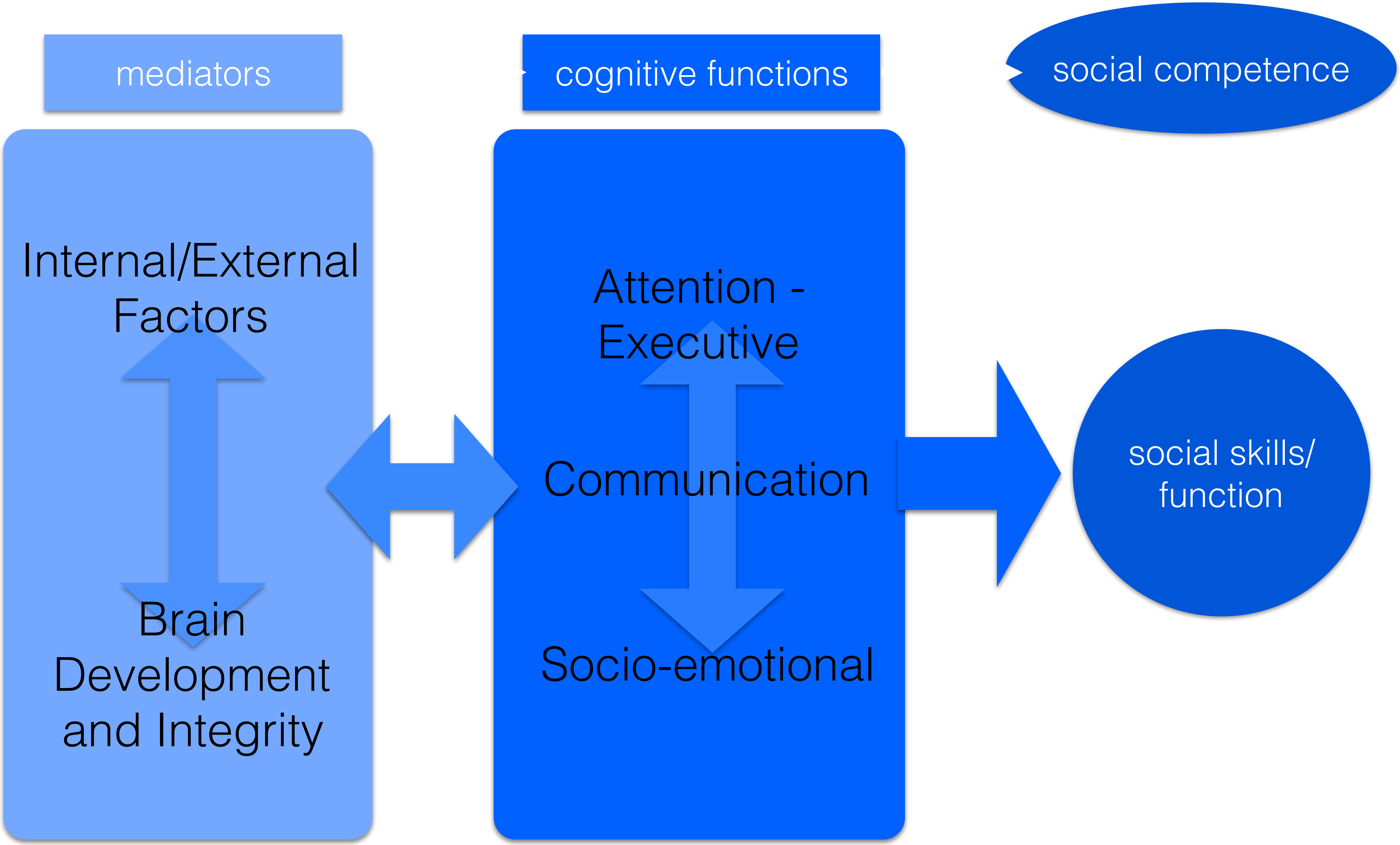
Theories of neurocognitive development

Example

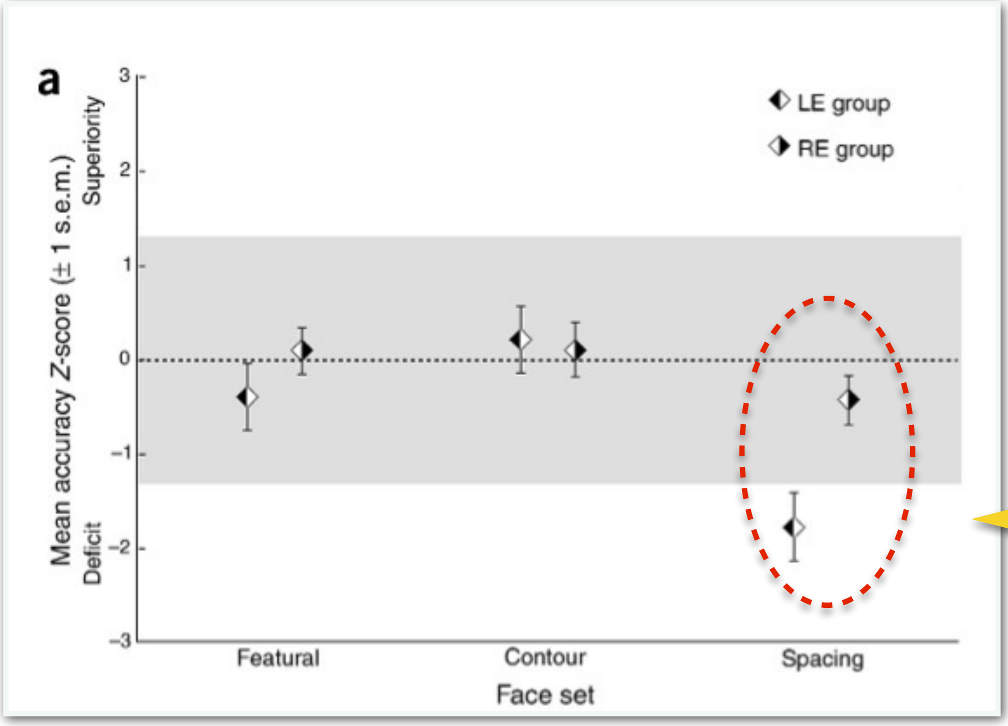
Example: social development



Beauchamp, M. H., & Anderson, V. (2010). SOCIAL: an integrative framework for the development of social skills. Psychological bulletin, 136(1), 39–64. doi:10.1037/a0017768

Internal factors

- visual ability



Participants with congenital visual deficits in the left hemi-field performed significantly worse

Participants had to judge similarity of faces that were manipulated to differ in the spacing between features

→ individuals that had no visual input to the right hemisphere during infancy perform sign. worse on the spacing task, which requires configural processing

Le Grand, R., Mondloch, C. J., Maurer, D., & Brent, H. P. (2003). Expert face processing requires visual input to the right hemisphere during infancy. Nature neuroscience, 6(10), 1108–1112. doi:10.1038/nn1121

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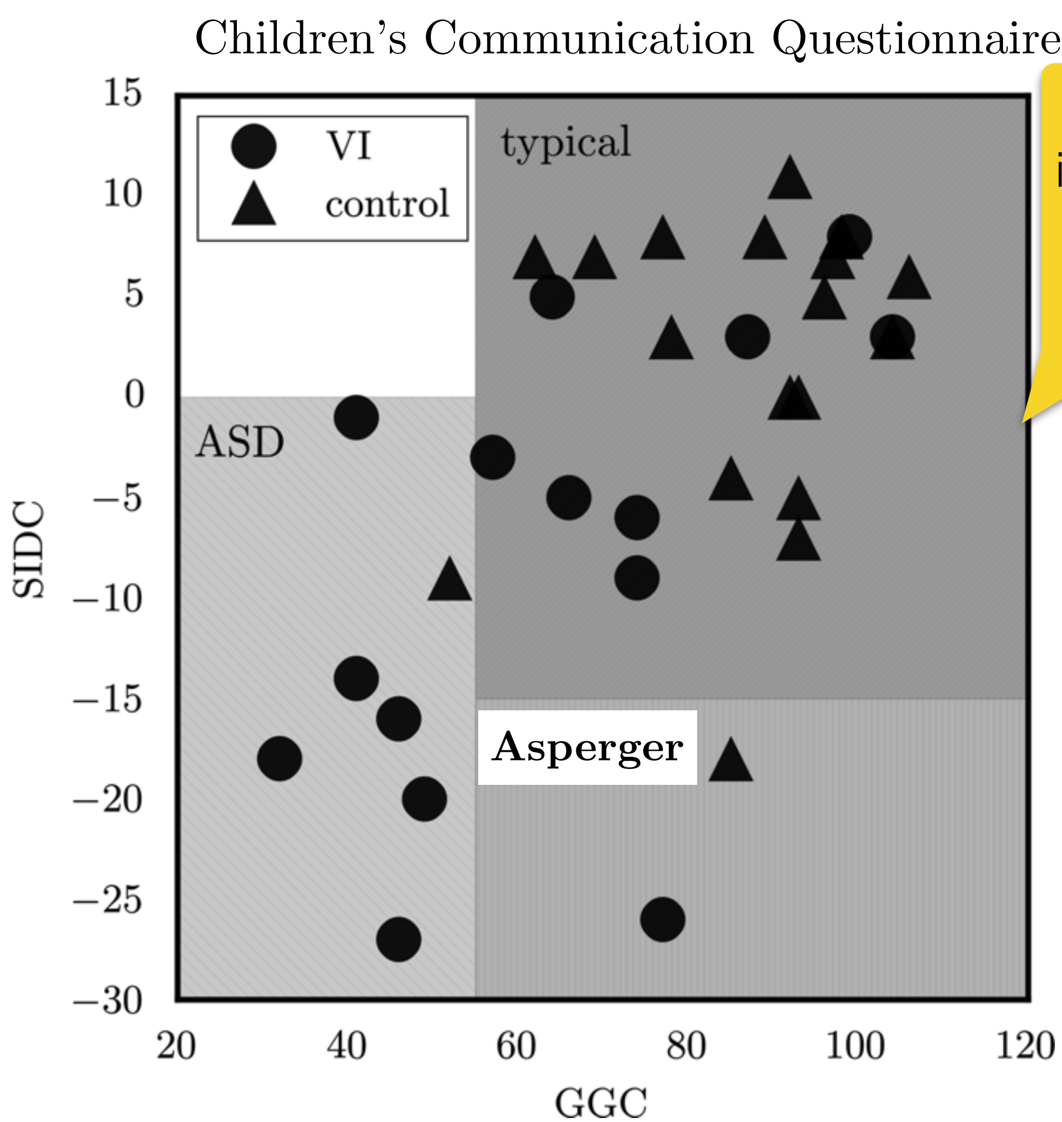
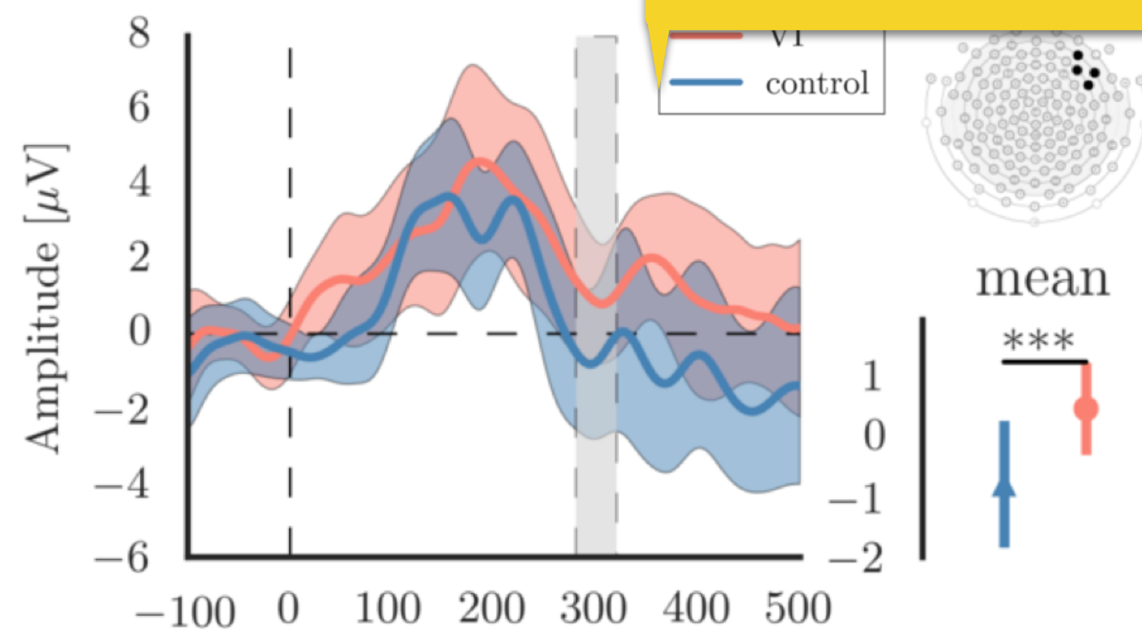
Example of cascading effects:
Social cognition in children with congenital visual impairment



Children with congenital visual impairment show communication deficits that are similar to typically-sighted children with ASD

They also show an attenuated response to own-name stimuli in an ERP experiment

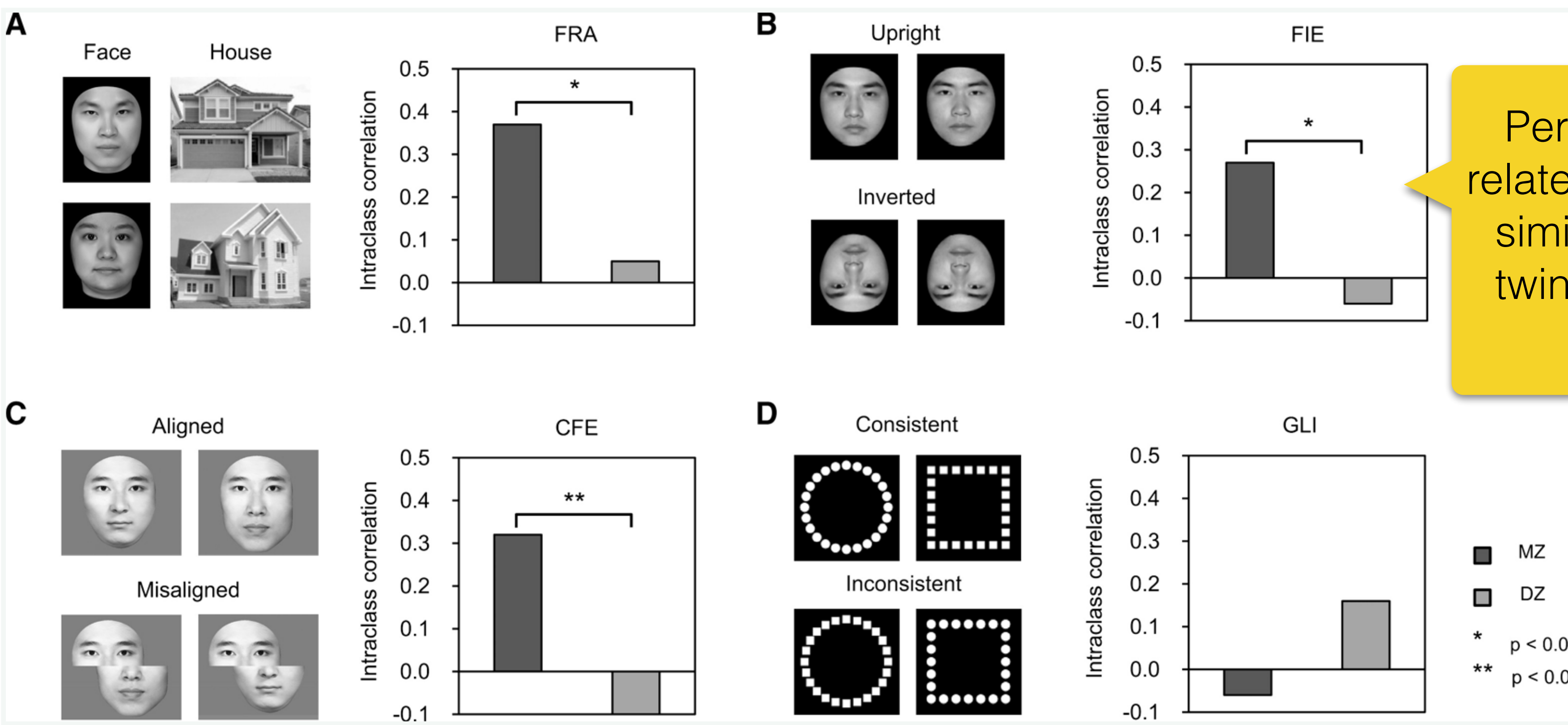


Bathelt, J., Dale, N. J., de Haan, M. (2017): “Event-related potential response to auditory social stimuli, parent-reported social communicative deficits and autism risk in school-aged children with congenital visual impairment“ Developmental Cognitive Neuroscience

Internal factors

- visual ability
- genetic predisposition

Intraclass correlation compared between monozygotic and dizygotic twins



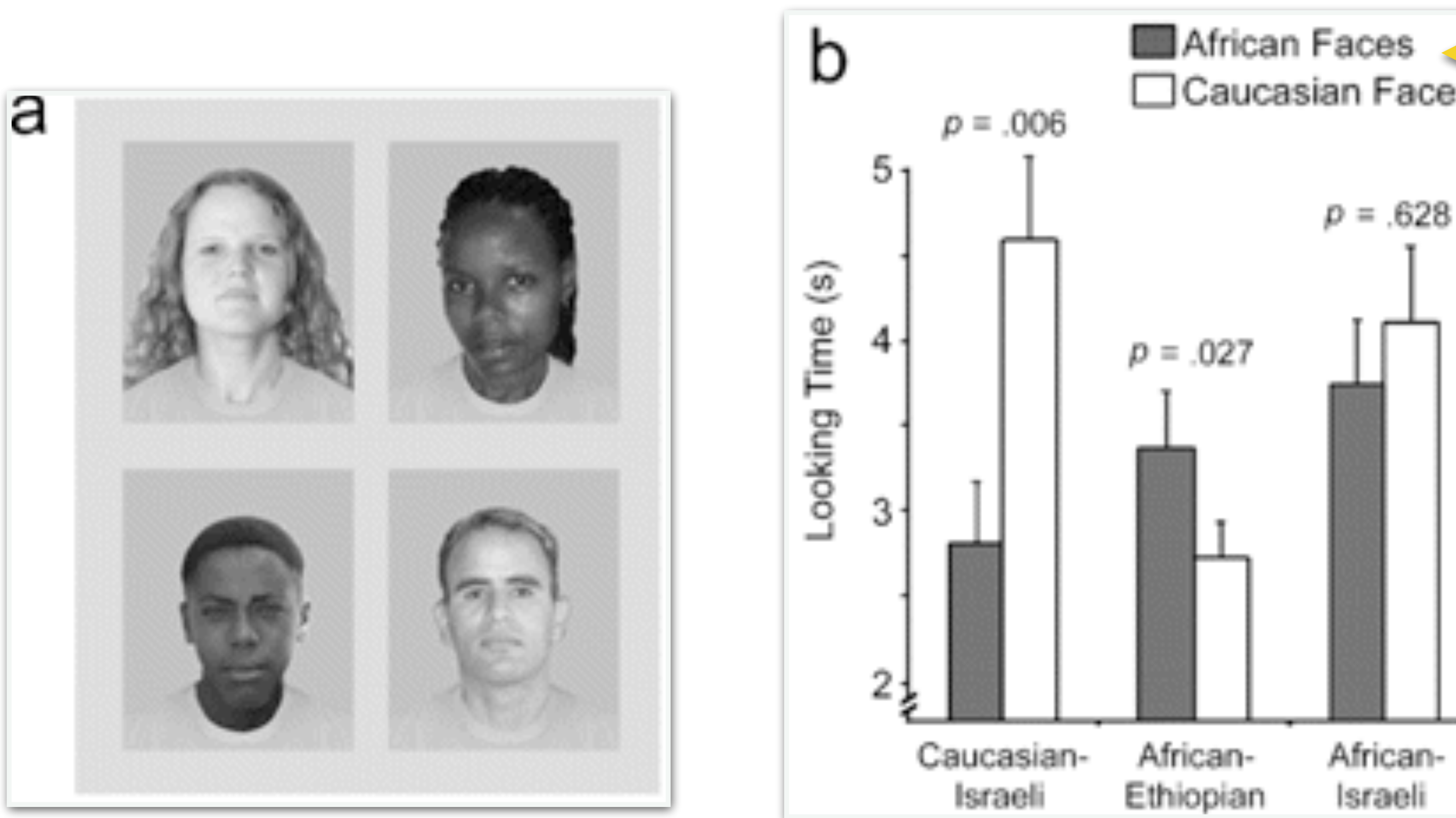
Performance of face-related task is sign. more similar in monozygotic twins than in dizygotic twins

→ the shared variability on face-specific tasks is higher in monozygotic compared to dizygotic twins

Zhu, Q., Song, Y., Hu, S., Li, X., Tian, M., Zhen, Z., et al. (2010). Heritability of the Specific Cognitive Ability of Face Perception. Current Biology, 20(2), 137–142. doi:10.1016/j.cub.2009.11.067

External factors

- **environmental influence**



Caucasian infants spent more time looking at Caucasian faces, African infants look longer at African faces; looking times do not differ for infants from a mixed environment —> exposure in the environment influences what infants attend to

→ infants' own-race bias depends on exposure in their environment

Bar-Haim, Y., Ziv, T., Lamy, D., & Hodes, R. M. (2006). Nature and nurture in own-race face processing. Psychological science, 17(2), 159–163. doi:10.1111/j.1467-9280.2006.01679.x

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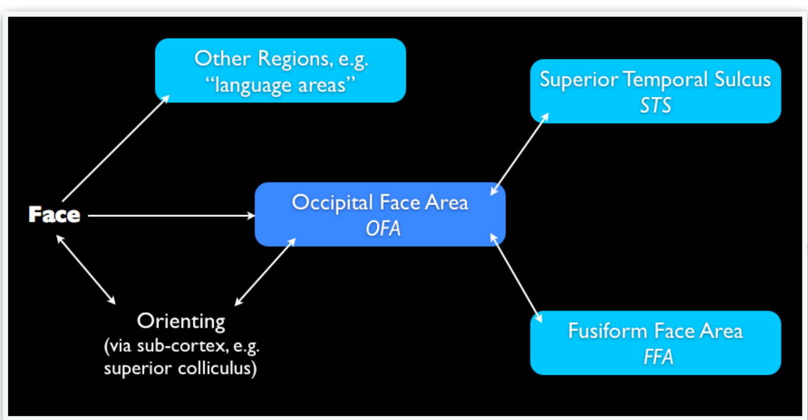
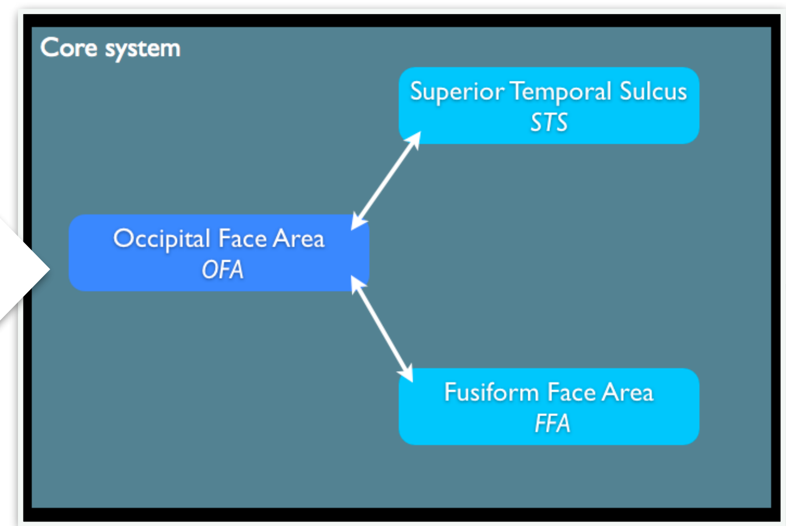
Development of the Face Processing System

Infancy



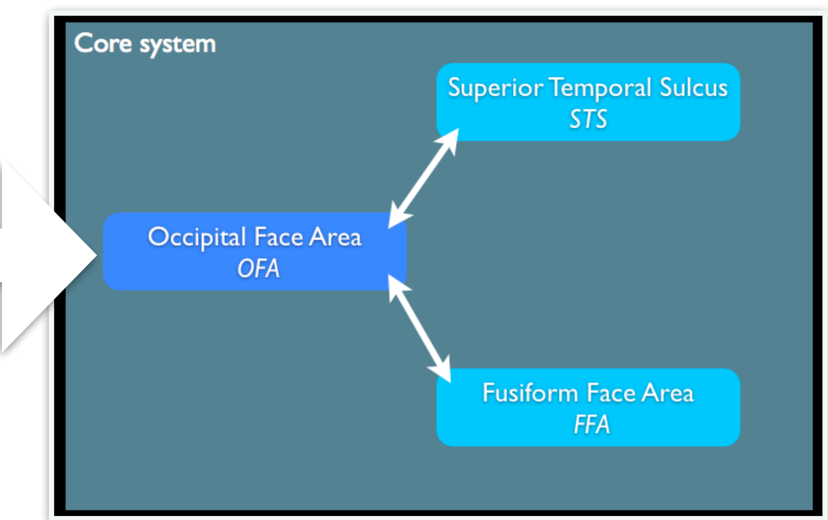
- subcortical mechanisms
- response biases

Childhood



- core cortical architecture
- not fully specialised

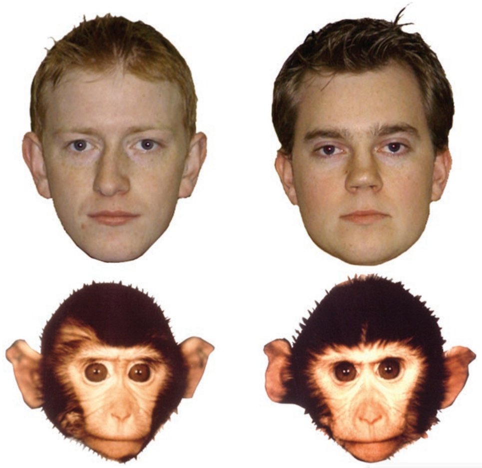
Adulthood



- specialised cortical network

Ward, J. (n.d.). The Student's Guide to Social Neuroscience (1st ed.). Psychology Press Hove, UK.

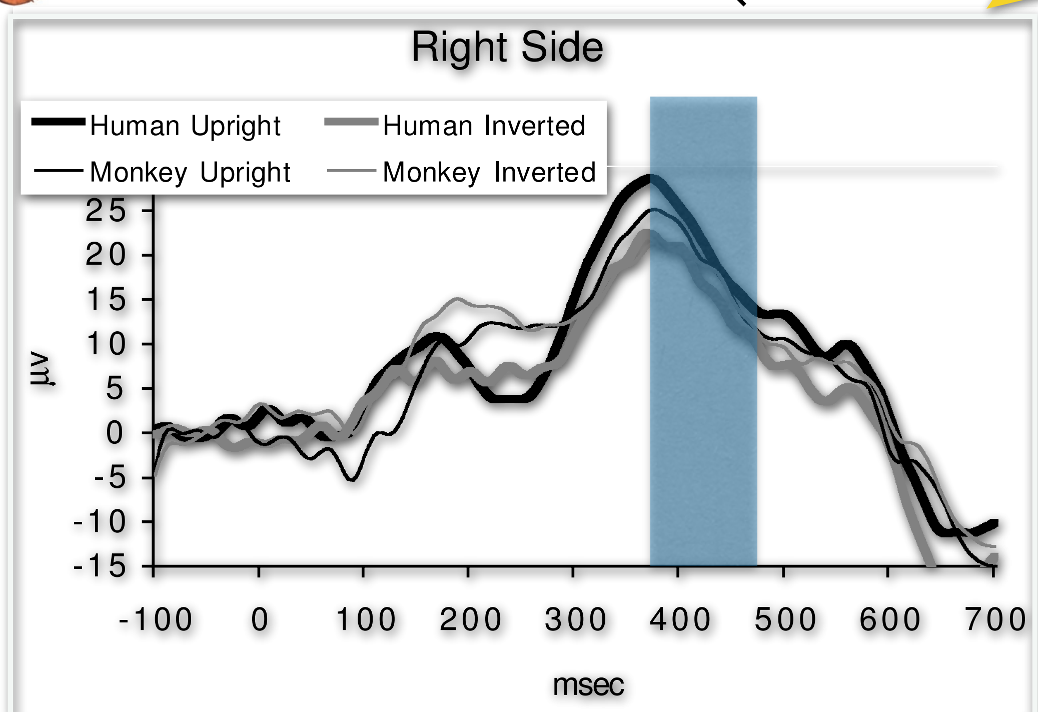
Perceptual Narrowing



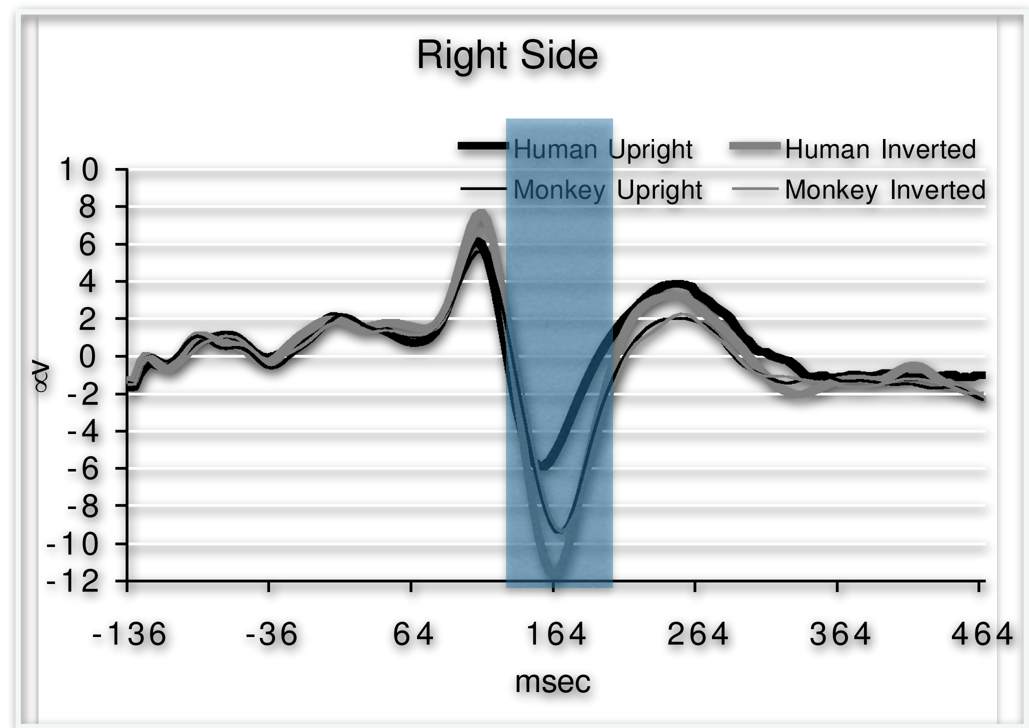
infant P400

The ERP shows a specific response to upright human faces in adults, but not in infants

adult N170



6 month-old infants

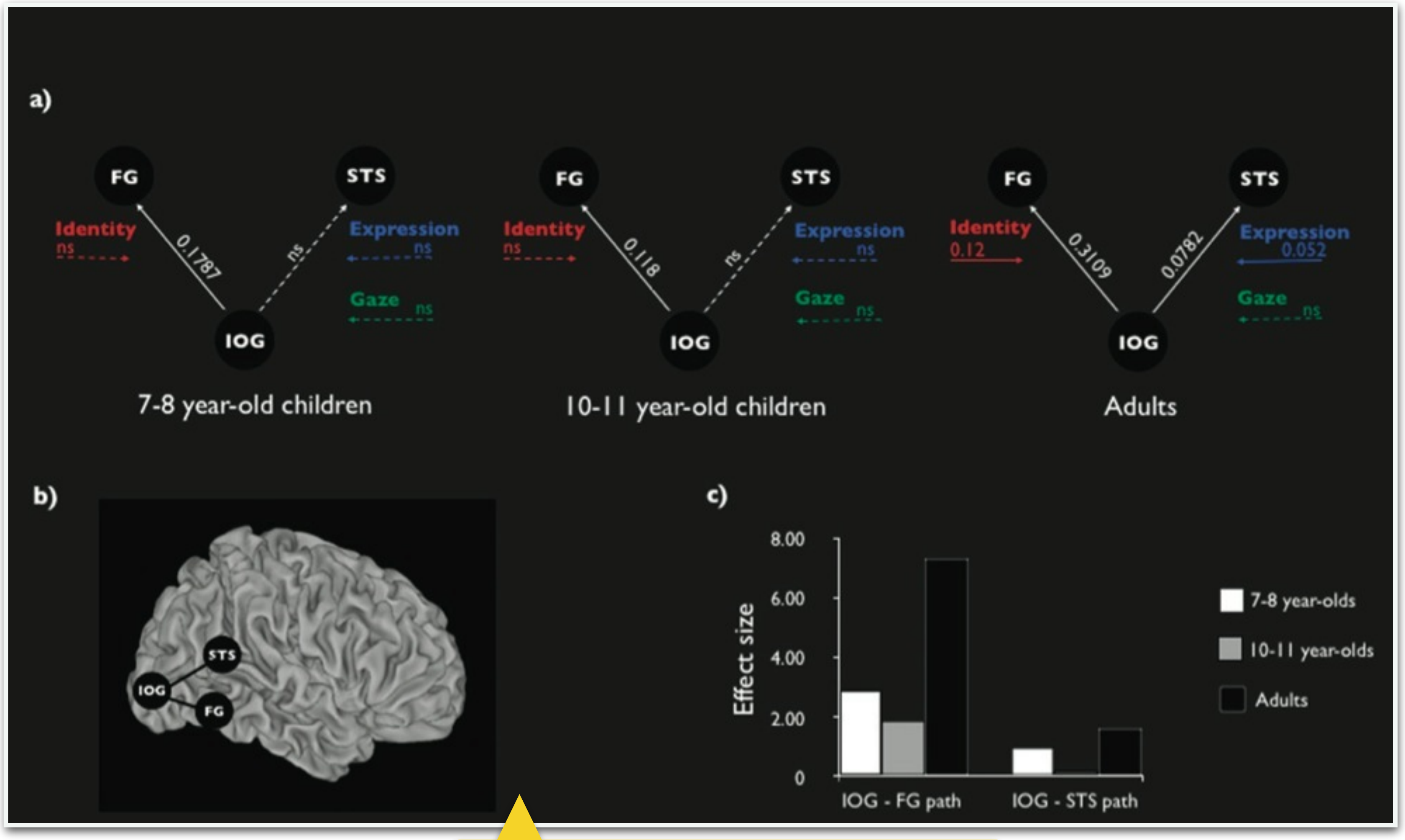


adults

→ the event-related potentials response indicates specialisation of neural substrates towards processing upright human faces

de Haan, M., Humphreys, K. & Johnson, M. H. Developing a brain specialized for face perception: a converging methods approach. Dev. Psychobiol. 40, 200–212 (2002).
Pascalis, O., de Haan, M. & Nelson, C. A. Is face processing species-specific during the first year of life? Science 296, 1321–1323 (2002).

Development between childhood and adulthood

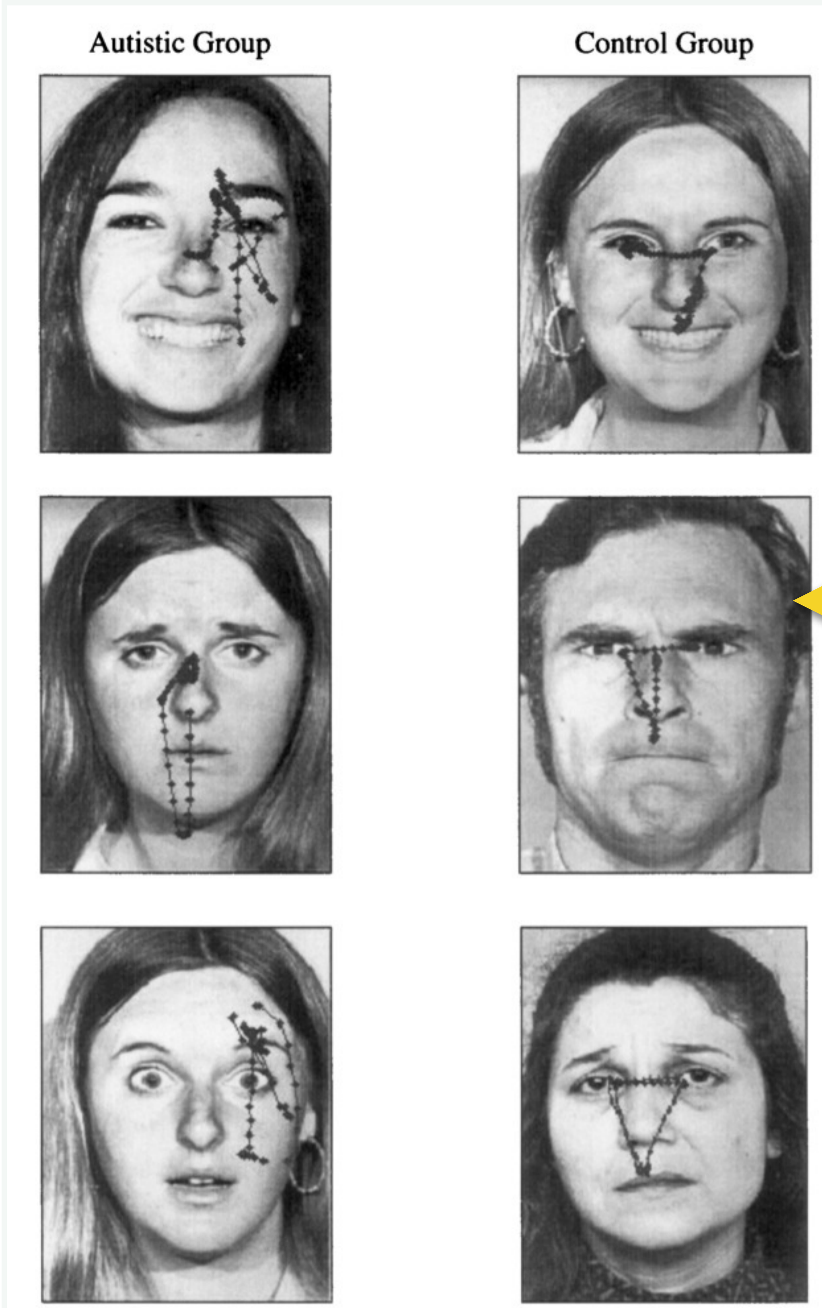


Connections between areas of the core face processing network increases between childhood and adulthood

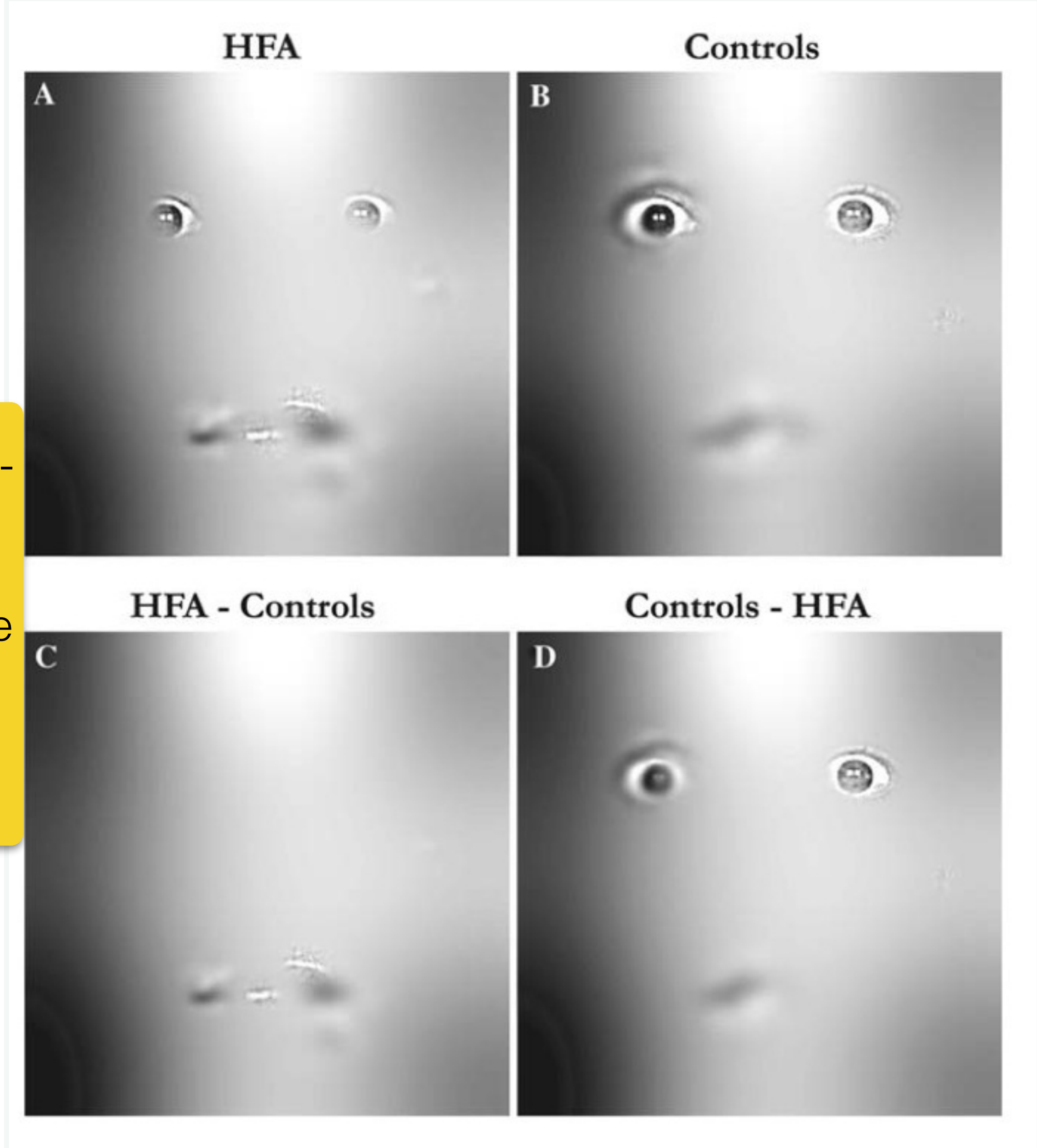
- DCM analysis:
  - indicates the connection strength between areas of interest
- connection between core face network areas is stronger in adults compared to adolescents and children

Cohen Kadosh, K., Cohen Kadosh, R., Dick, F., & Johnson, M. H. (2011). Developmental Changes in Effective Connectivity in the Emerging Core Face Network. Cerebral cortex (New York, N.Y. : 1991), 1–6. doi:10.1093/cercor/bhq215

Eye tracking studies of adults with high-functioning autism (HFA):



Adults with high-functioning autism deviate from typical face scanning observed in typical adults



Pelphrey, K. A., Sasson, N. J., Reznick, J. S., Paul, G., Goldman, B. D., & Piven, J. (2002). Visual Scanning of Faces in Autism - Springer. Journal of Autism and Developmental Disorders, 32(4), 249–261. doi:10.1023/A:1016374617369

Spezio, M. L., Adolphs, R., Hurley, R. S. E., & Piven, J. (2006). Abnormal Use of Facial Information in High-Functioning Autism. Journal of Autism and Developmental Disorders, 37(5), 929–939. doi:10.1007/s10803-006-0232-9

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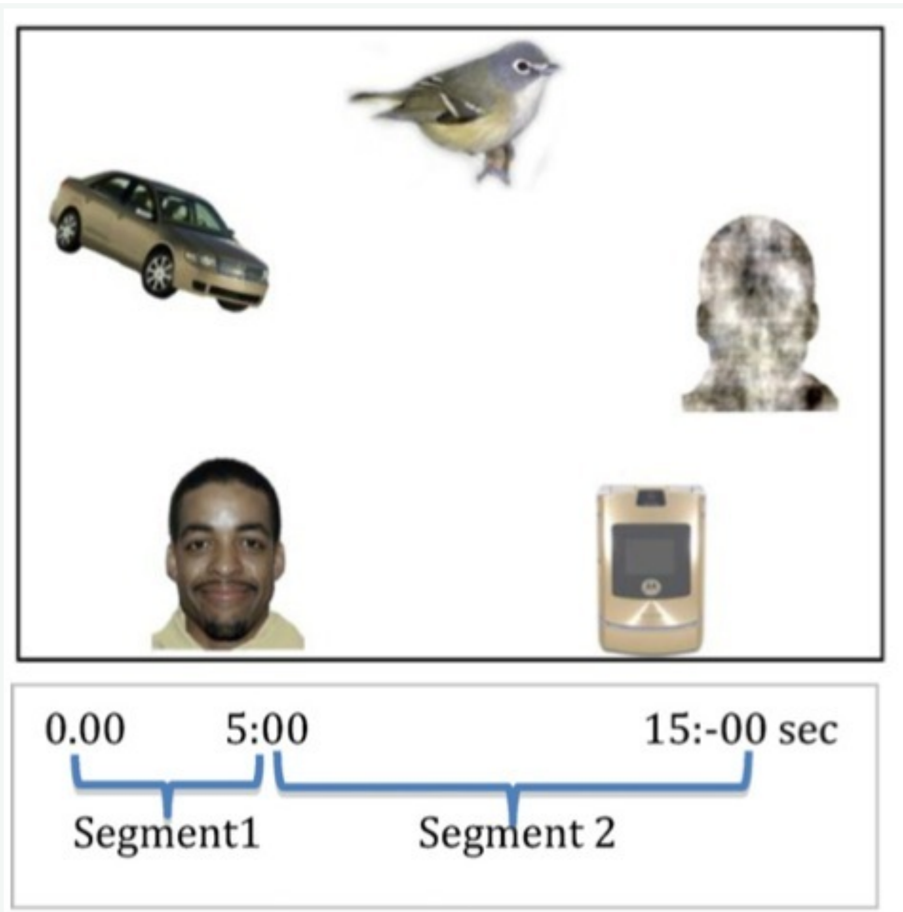
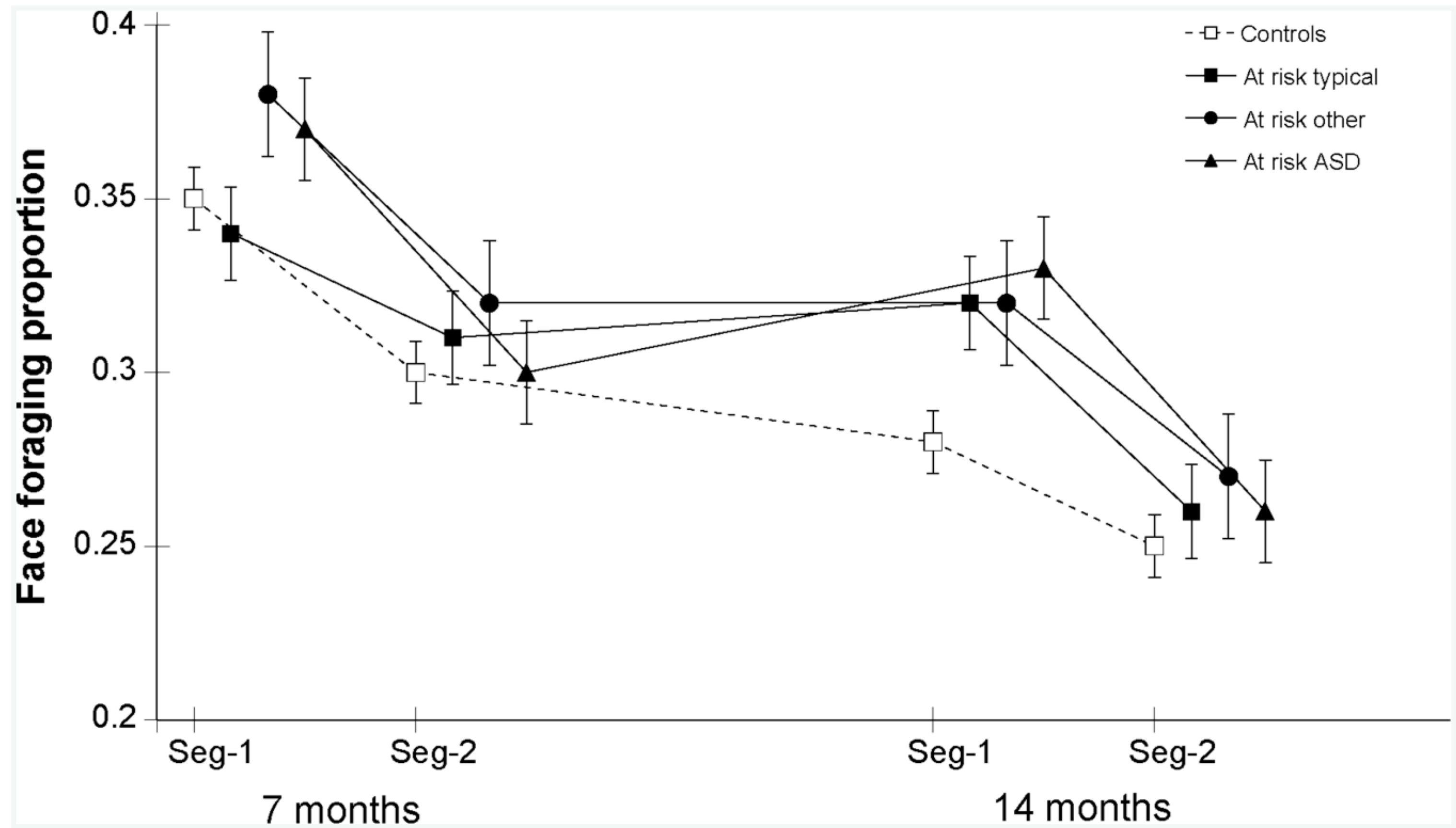
Orienting to face and non-face stimuli in infants at risk for autism:





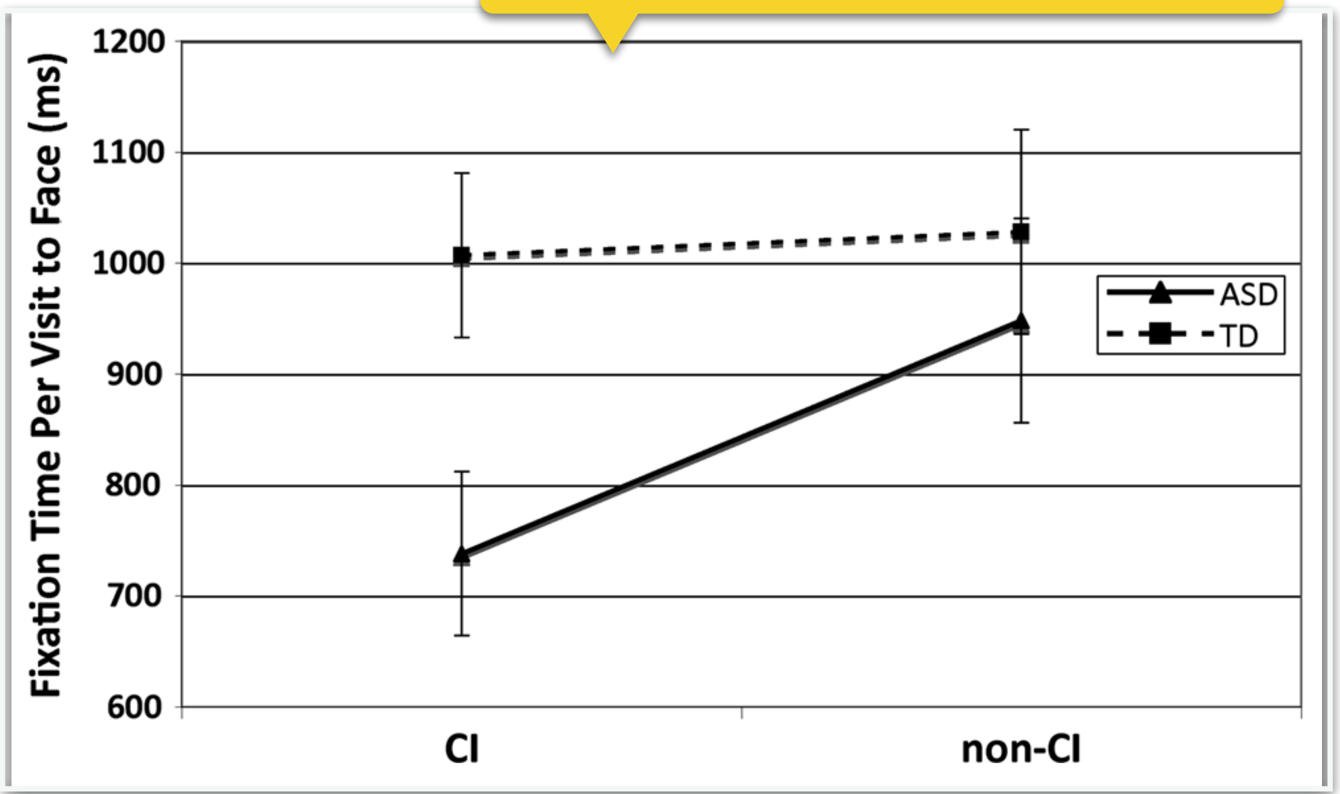
→ infants at risk for ASD spent more time (!) looking at faces compared to the control group

Elsabbagh, M., Gliga, T., Pickles, A., Hudry, K., Charman, T., Johnson, M. H., the BASIS Team. (2012). The development of face orienting mechanisms in infants at-risk for autism. Behavioural Brain Research. doi:10.1016/j.bbr.2012.07.030

object of
"circumscribed interest"
(CI)

non-CI object

The looking time in pre-schoolers with ASD seems to depend on the stimuli used



Time spent looking at face stimulus when paired with a CI or non-CI stimulus

→ infants between 24 and 36 months with ASD spent sign. less time looking at face stimulus when a circumscribed interest competing stimulus was presented

Sasson, N. J. & Touchstone, E. W. Visual attention to competing social and object images by preschool children with autism spectrum disorder. J Autism Dev Disord 44, 584–592 (2014).

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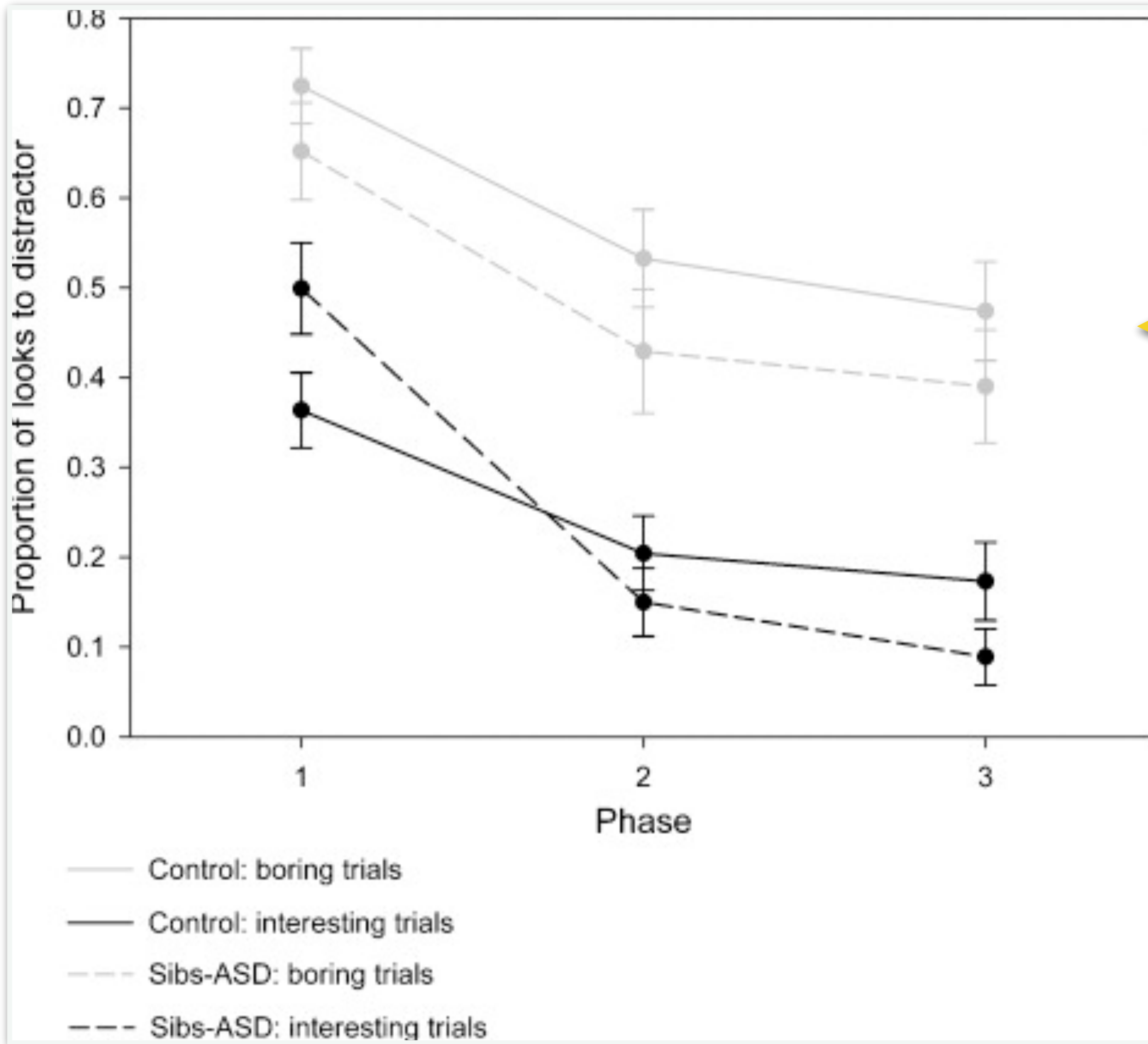
Visual attention shifting in infants at risk for ASD

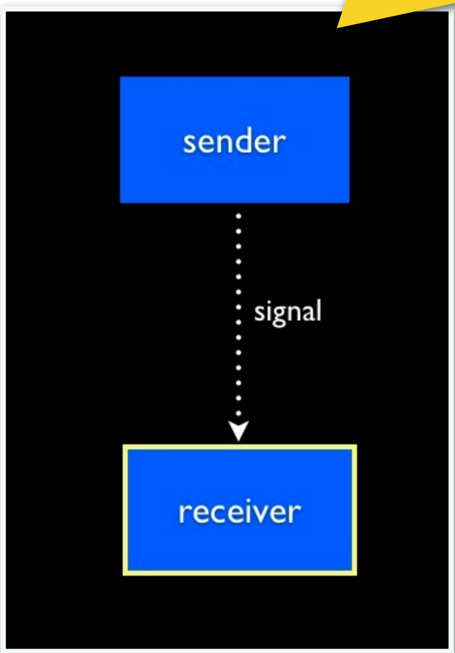


Perhaps, there is a general difference in visual attention in infants with high ASD risk —> spent more time looking at individual stimuli (sticky attention)

→ infants at risk for ASD show less visual disengagement
→ there is a difference in attention allocation/shifting in infants with ASD

Holmboe, K., Elsabbagh, M., Volein, A., Tucker, L. A., Baron-Cohen, S., Bolton, P., et al. (2010). Frontal cortex functioning in the infant broader autism phenotype. Infant Behavior and Development, 33(4), 482–491.

Communication depends on the ability of the sender to generate an appropriate signal, the signal to reach the receiver, and the receiver to adequately decode the signal



- faces are an important source of information for infants
- attention to faces is linked to important developmental outcomes in infants
- joint-referencing and shared gaze rely on communication with the caregiver through facial cues
- developmental disorders, e.g. autism spectrum disorder, show alterations in these behaviours

“Baby faces may hold key to Autism diagnosis” (2009) featuring Prof. Charles Nelson, Harvard Children’s Hospital

Communication

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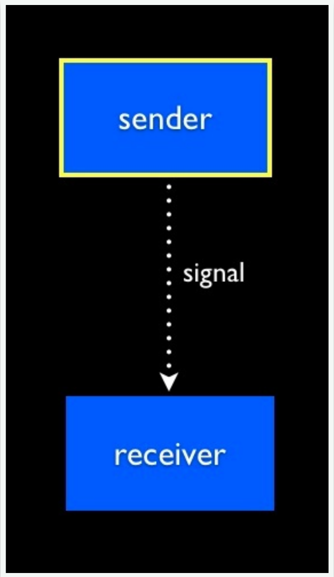


Communication difficulties

- Möbius syndrome: congenital facial paralysis

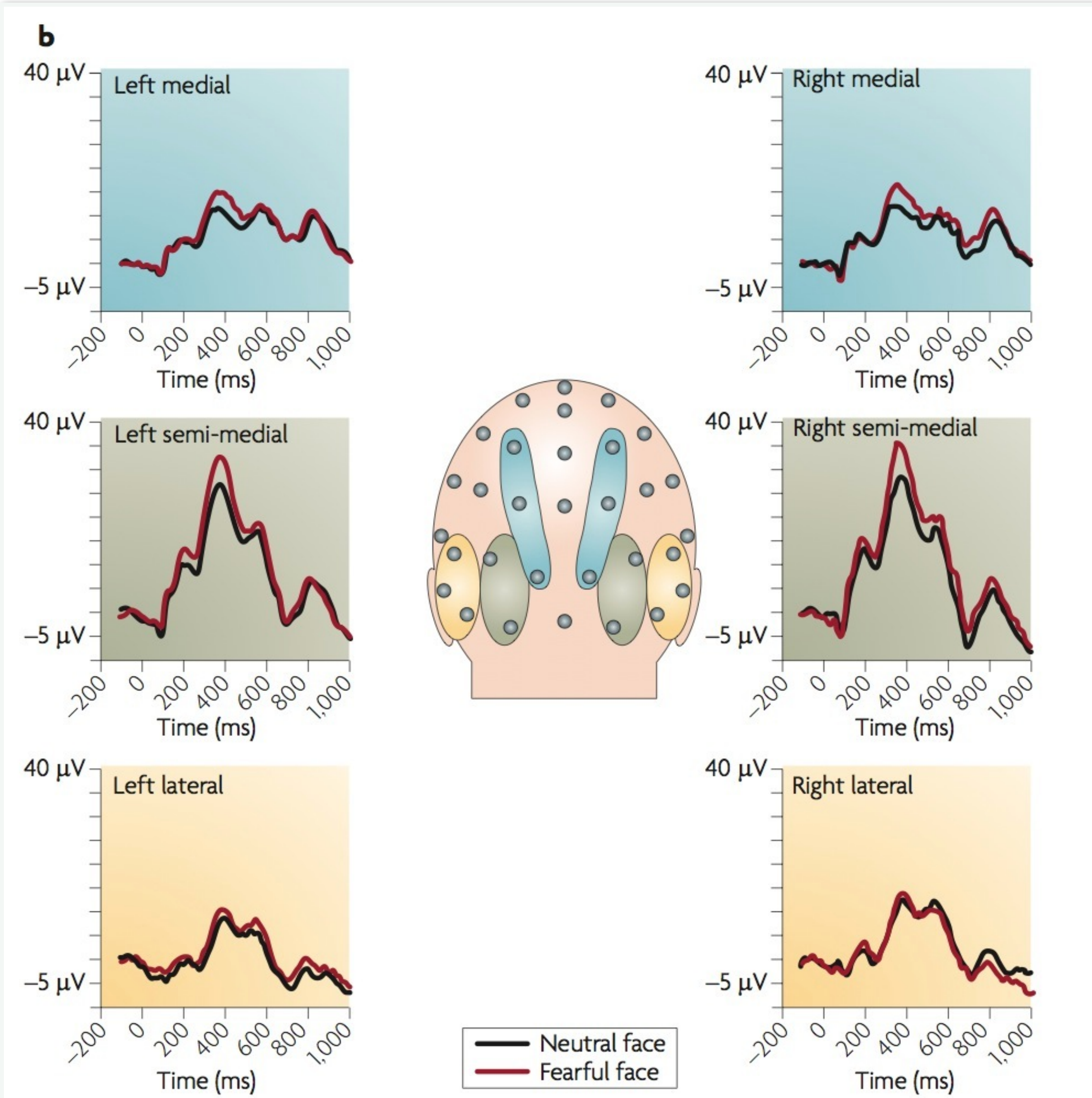
TABLE 1 Variable Descriptive Statistics, *t* Tests, and Effect Sizes

Measure	*Group*	*Mean*	*SD*	*t (df)*	*Significance (One-Tailed)*	*Effect Size (r)*
Age	Moebius	37.73	13.70	0.79 (72)	.43 (two-tailed)	.09
	Control	35.32	12.47			
Social competence	Moebius	36.35	10.37	−1.75 (72)	.04	.20
	Control	40.22	8.58			
	Norm data	40.65	9.32	−2.52 (36)	.01	.38
Anxiety	Moebius	7.89	3.85	0.67 (72)	.25	.07
	Control	7.32	3.49			
Depression	Moebius	3.95	3.60	−0.56 (72)	.29	.06
	Control	4.35	2.52			
Satisfaction with life	Moebius	21.62	7.20	−0.62 (72)	.27	.07
	Control	22.65	7.20			
	Norm data	23.5	6.43	−1.59 (36)	.06	.26
Facial Emotion Communication Questionnaire	Moebius	16.19	6.53	−8.19 (51)*	.00	.75
	Control	25.89	3.05			

* Equal variances not assumed.

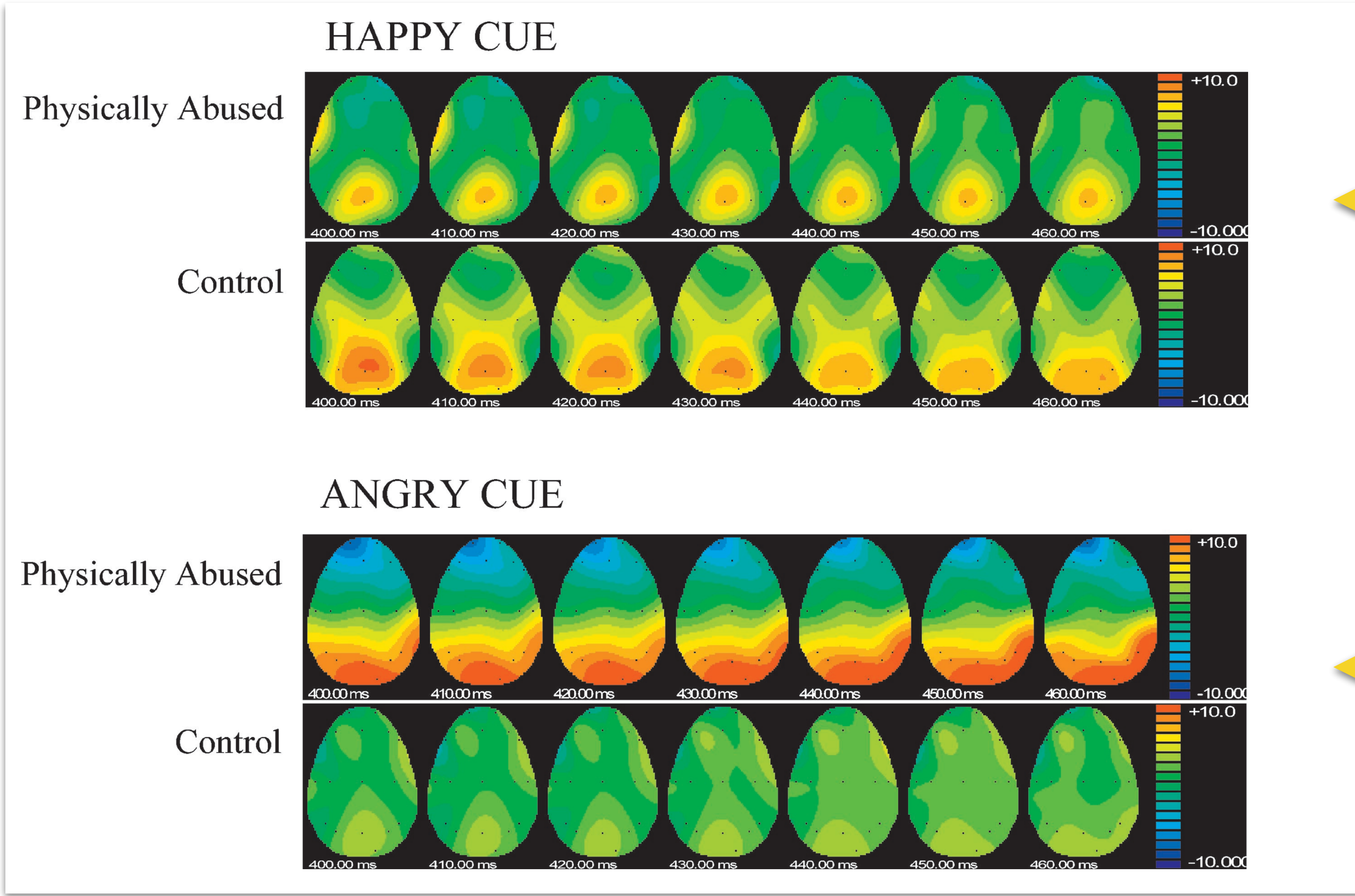
→ the ability to produce facial expressions influences social competence

Bogart, K. R., & Matsumoto, D. (2010). Living With Moebius Syndrome: Adjustment, Social Competence, and Satisfaction With Life. The Cleft Palate-Craniofacial Journal, 47(2), 134–142. doi:10.1597/08-257.1



→ adults show enhanced ERP amplitude in response to emotional faces compared to neutral

Leppänen, J. M., & Nelson, C. A. (2009). Tuning the developing brain to social signals of emotions. Ten years of Nature Reviews Neuroscience: insights from the highly cited, 10, 37–47. doi:10.1038/nrn2554



Children with a history of physical abuse show an attenuated response to happy faces

and an enhanced response to angry faces

Topographic representation of ERP to angry and happy face cues in children with physical abuse history and a control group

Pollak, S. D. & Tolley-Schell, S. A. Selective attention to facial emotion in physically abused children. J Abnorm Psychol 112, 323–338 (2003).

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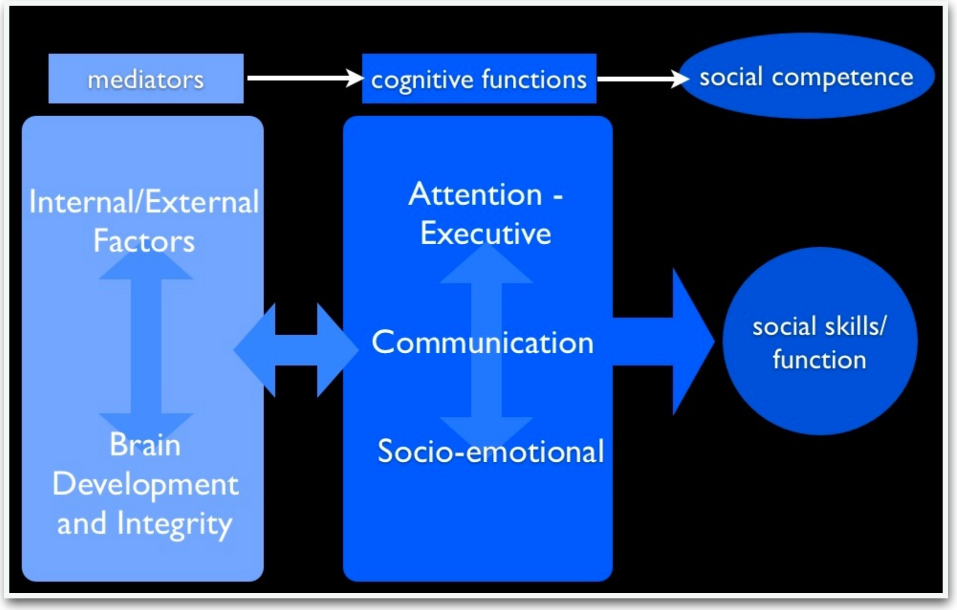
Example Summary



- **different levels of observation interact**:
  - internal/external factors interact with brain development , which leads to differences in behaviour that shape the future development of the system further
- neurodevelopmental studies need to take **different levels** of observation and **interactions within and between** these levels into account

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Recommended Reading

Di Martino, A., Fair, D. A., Kelly, C., Satterthwaite, T. D., Castellanos, F. X., Thomason, M. E., et al. (2014). Unraveling the miswired connectome: A developmental perspective. Neuron, 83(6), 1335–1353. http://doi.org/10.1016/j.neuron.2014.08.050

Johnson, M. H., de Haan, M. (2015). Developmental Cognitive Neuroscience. 4th ed. Hoboken, NJ: Wiley-Blackwell

Johnson, M. H. Executive function and developmental disorders: the flip side of the coin. Trends in Cognitive Sciences 16, 454–457 (2012). http://doi.org/10.1016/j.tics.2012.07.001

Leppänen, J. M., & Nelson, C. A. (2009). Tuning the developing brain to social signals of emotions. Ten years of Nature Reviews Neuroscience: insights from the highly cited, 10, 37–47. http://doi.org/10.1038/nrn2554

Power, J. D., Fair, D. A., Schlaggar, B. L., & Petersen, S. E. (2010). The Development of Human Functional Brain Networks. Neuron, 67(5), 735–748. http://doi.org/10.1016/j.neuron.2010.08.017

Somerville, L. H. (2016). Searching for Signatures of Brain Maturity: What Are We Searching For? Neuron, 92(6), 1164–1167. http://doi.org/10.1016/j.neuron.2016.10.059

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