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From Errors to Meaning: How education shapes the development of error perception, creative thinking, social engagement and self-consciousness in schoolchildren

CHUV · UNIL | Université de Lausanne · EPFL · UNIVERSITÉ DE GENÈVE · HUG Hôpitaux Universitaires Genève

CIBM.CH

Solange Denervaud, Ph.D.

Motivation to learn and to *engage* with daily life differ… WHY?

Are they better *performers* ?

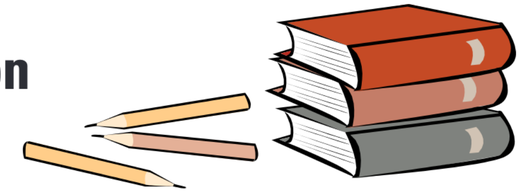
EDUCATIONFORUM

THE EARLY YEARS

Evaluating Montessori Education

Angeline Lillard[1]* and Nicole Else-Quest[2]

An analysis of students' academic and social scores compares a Montessori school with other elementary school education programs.



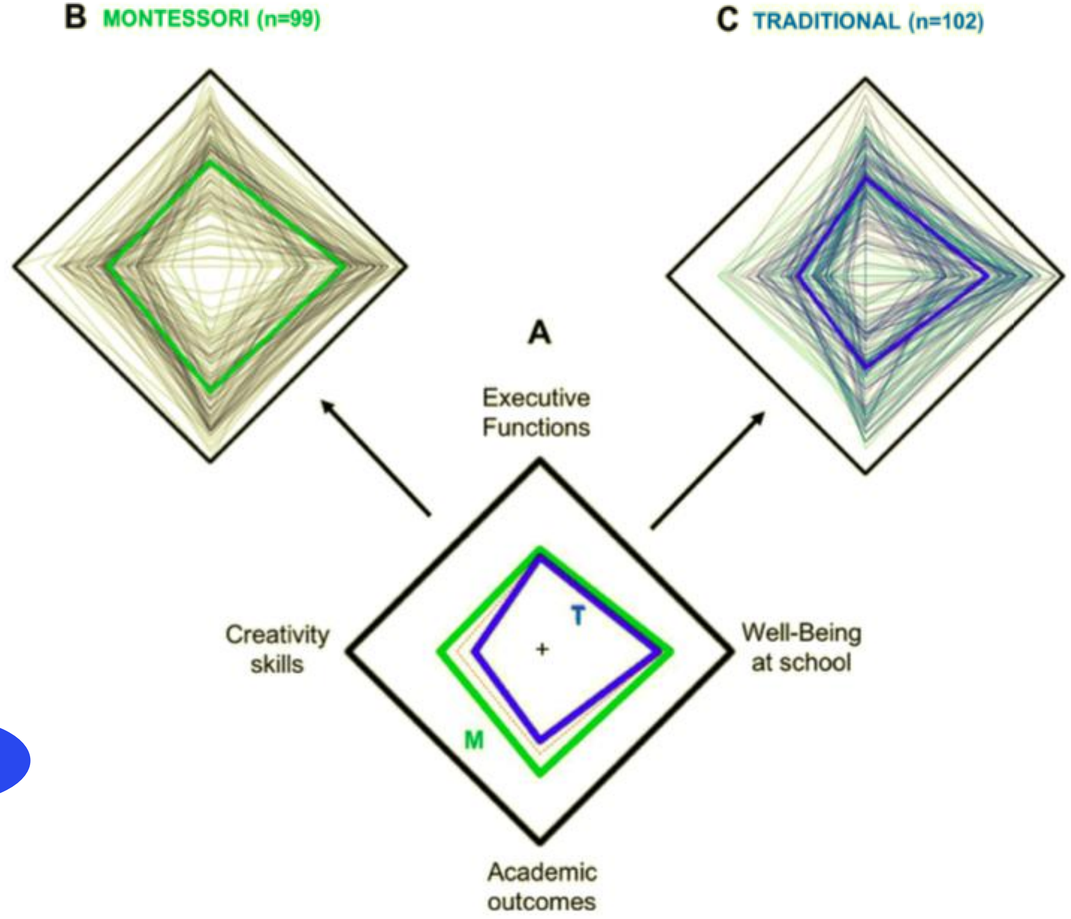
REVIEW

Interventions Shown to Aid Executive Function Development in Children 4 to 12 Years Old

Adele Diamond[1]* and Kathleen Lee[1]

Higher ‘executive functions’ ?

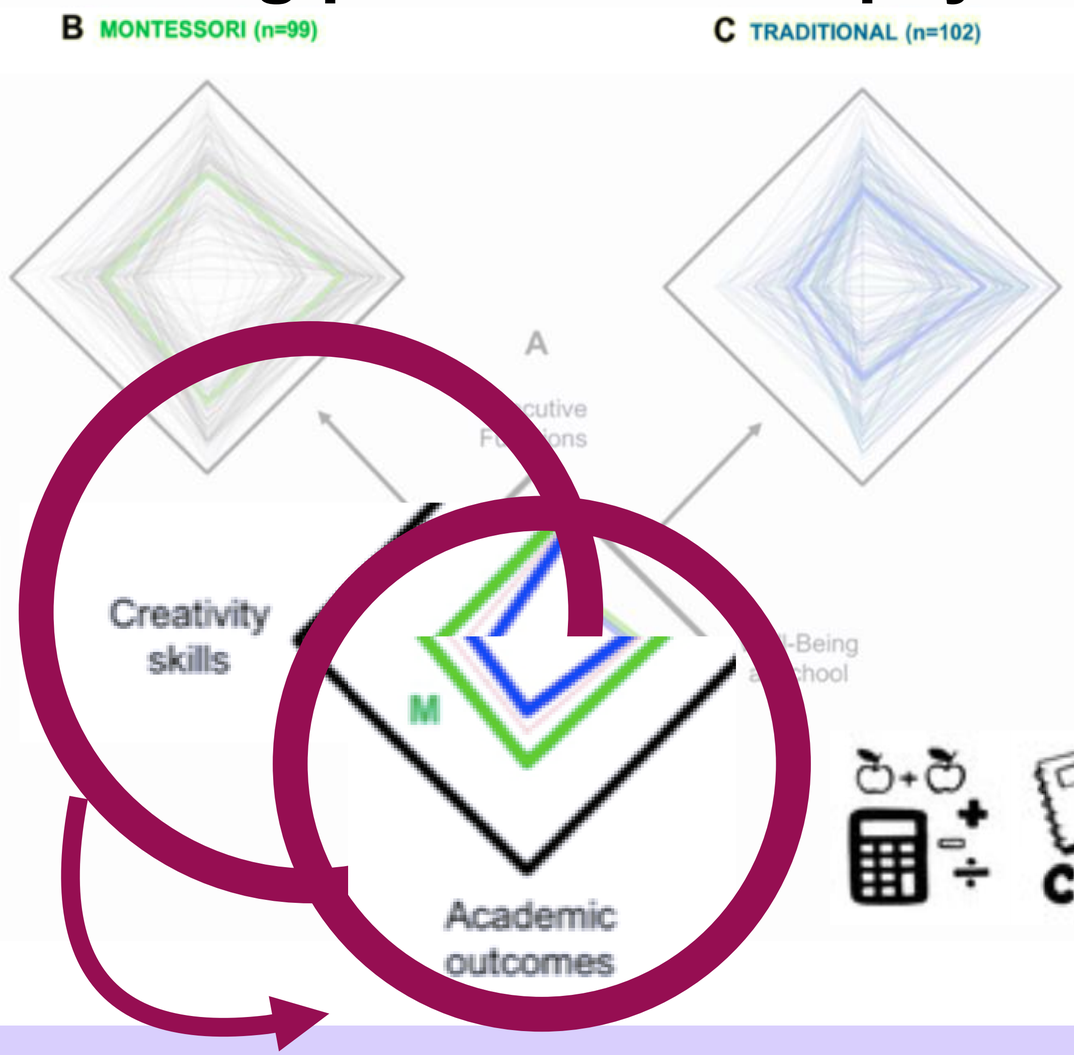
Replicating and extending past studies in psychological sciences



Denervaud, Knebel, Hagmann, & Gentaz, 2019

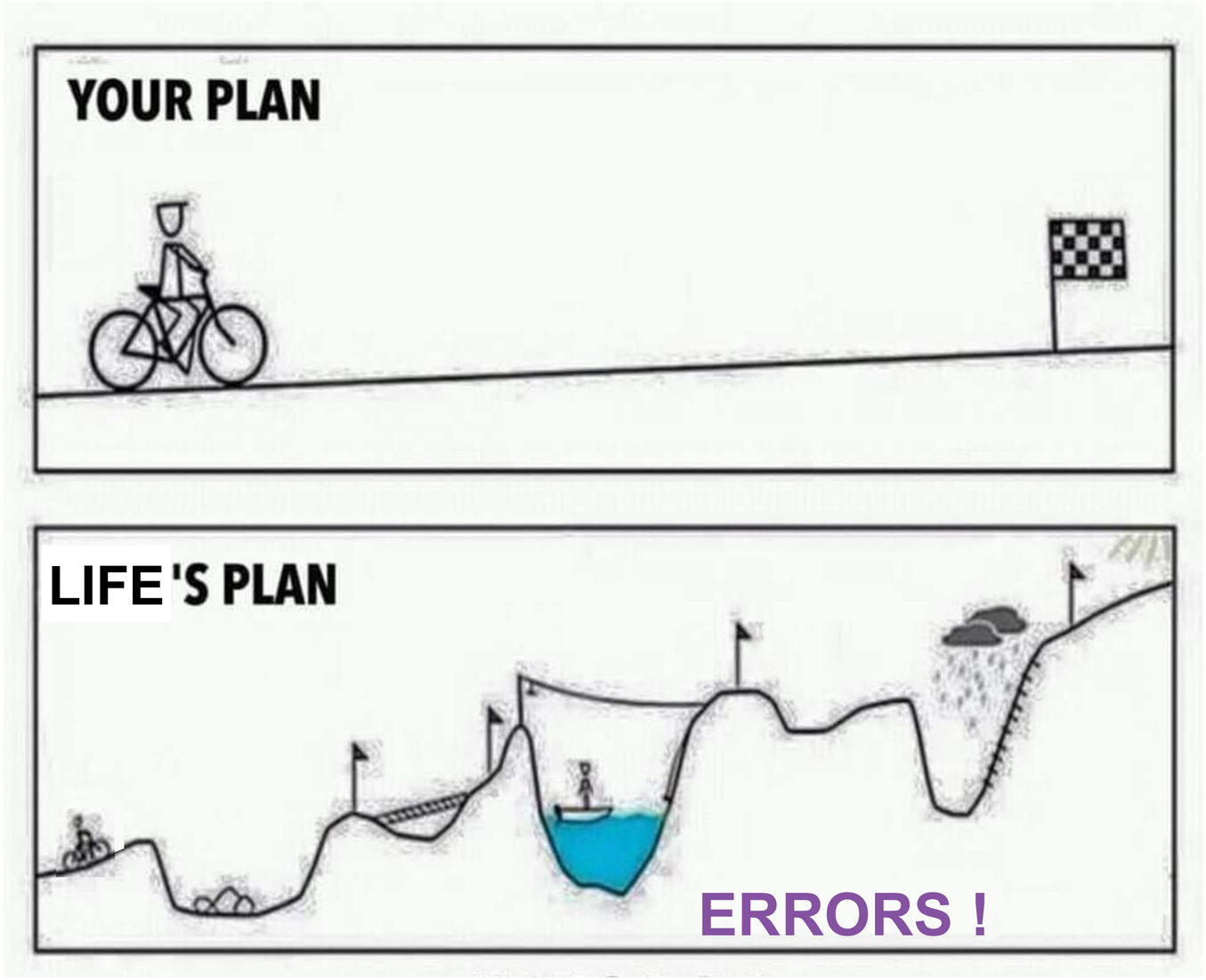
Higher ‘executive functions’ ?

Replicating and extending past studies in psychological sciences



Denervaud, Knebel, Hagmann, & Gentaz, 2019

What is *adaptability* ?



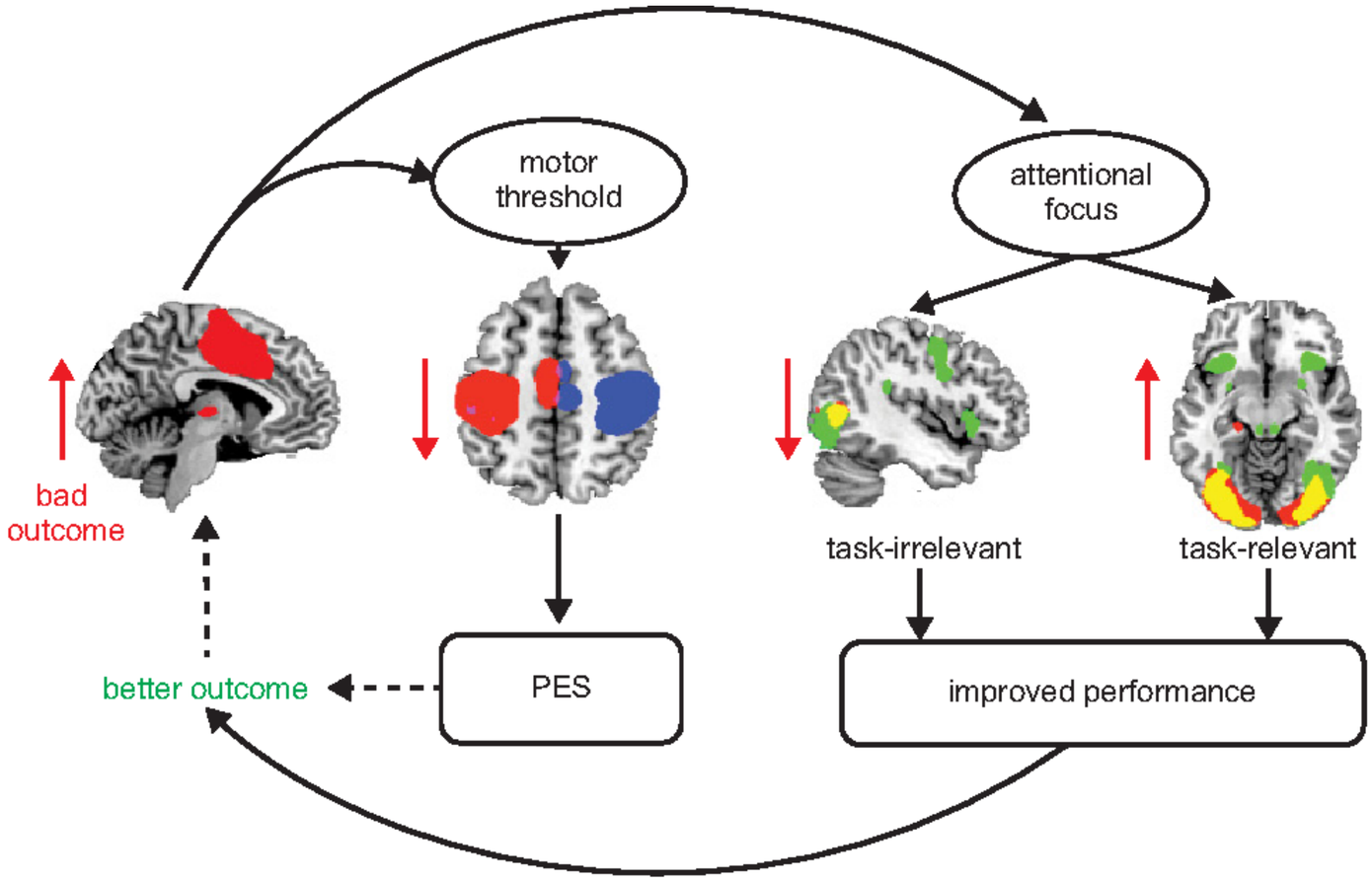
ERRORS !

> ADAPTATION

Error management

A 3-steps mechanism

- **Detection** of error
- **Integration** of novel information
  - *Slowing down*
  - *Senses are more sensitive*
  - *Need for repetition* ***to collect data***
- **Adaptation/Learning**



Ullsperger, Danielmeier, & Jocham, 2012

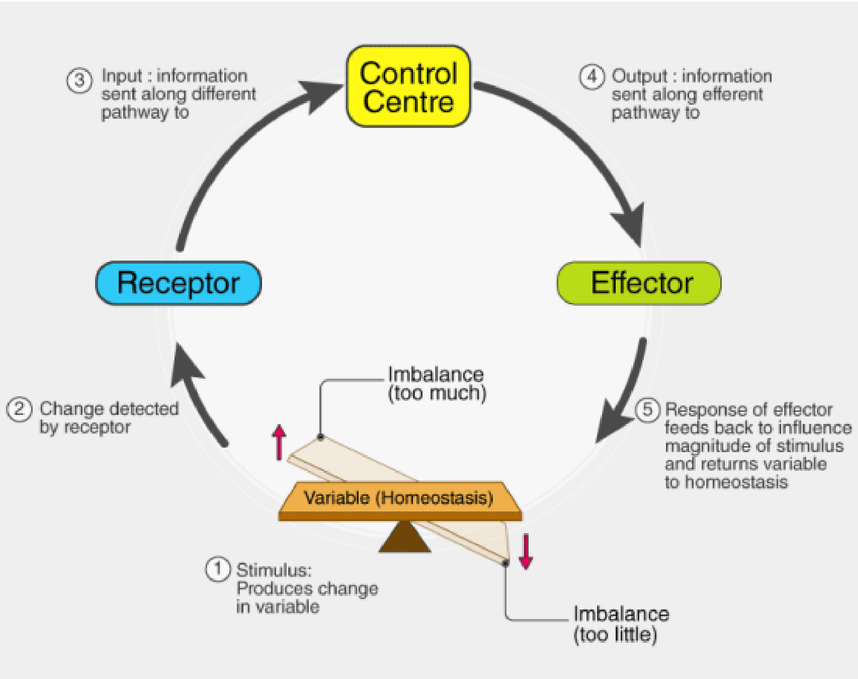
Error management

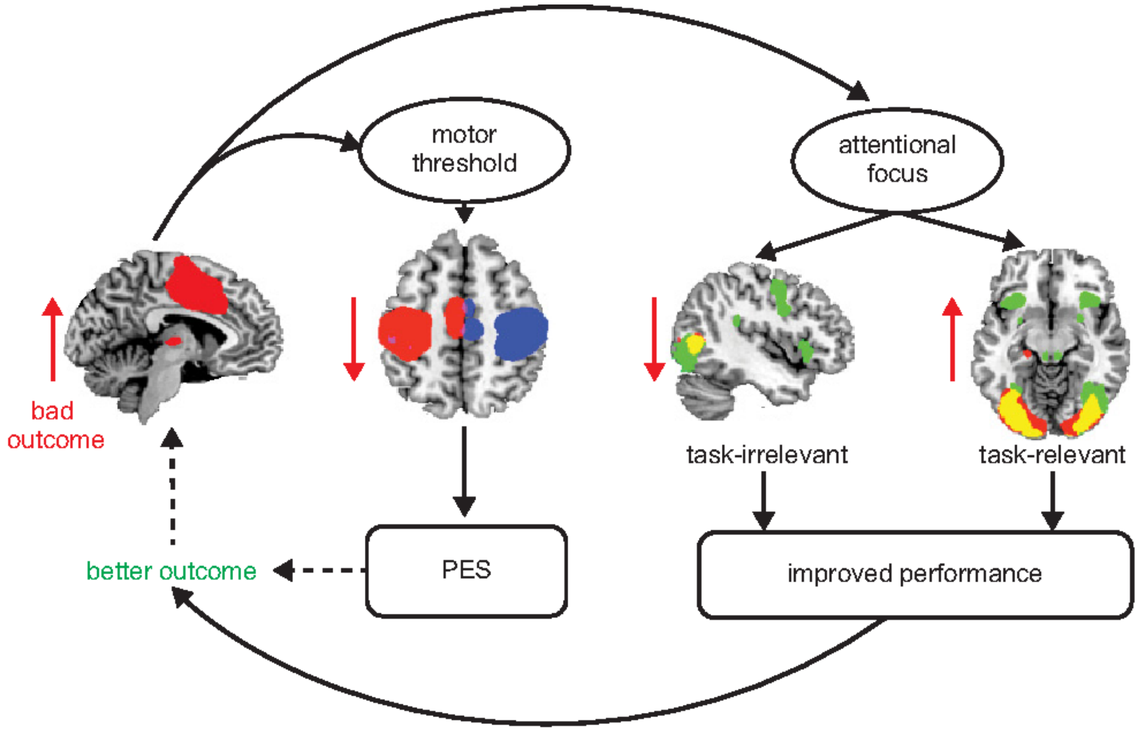
Error management

Thanks to the Anterior Cingulate Cortex (ACC)

The actualising tendency

The organism's single intrinsic drive to maintain, grow, and fulfil its potential — given the right conditions.



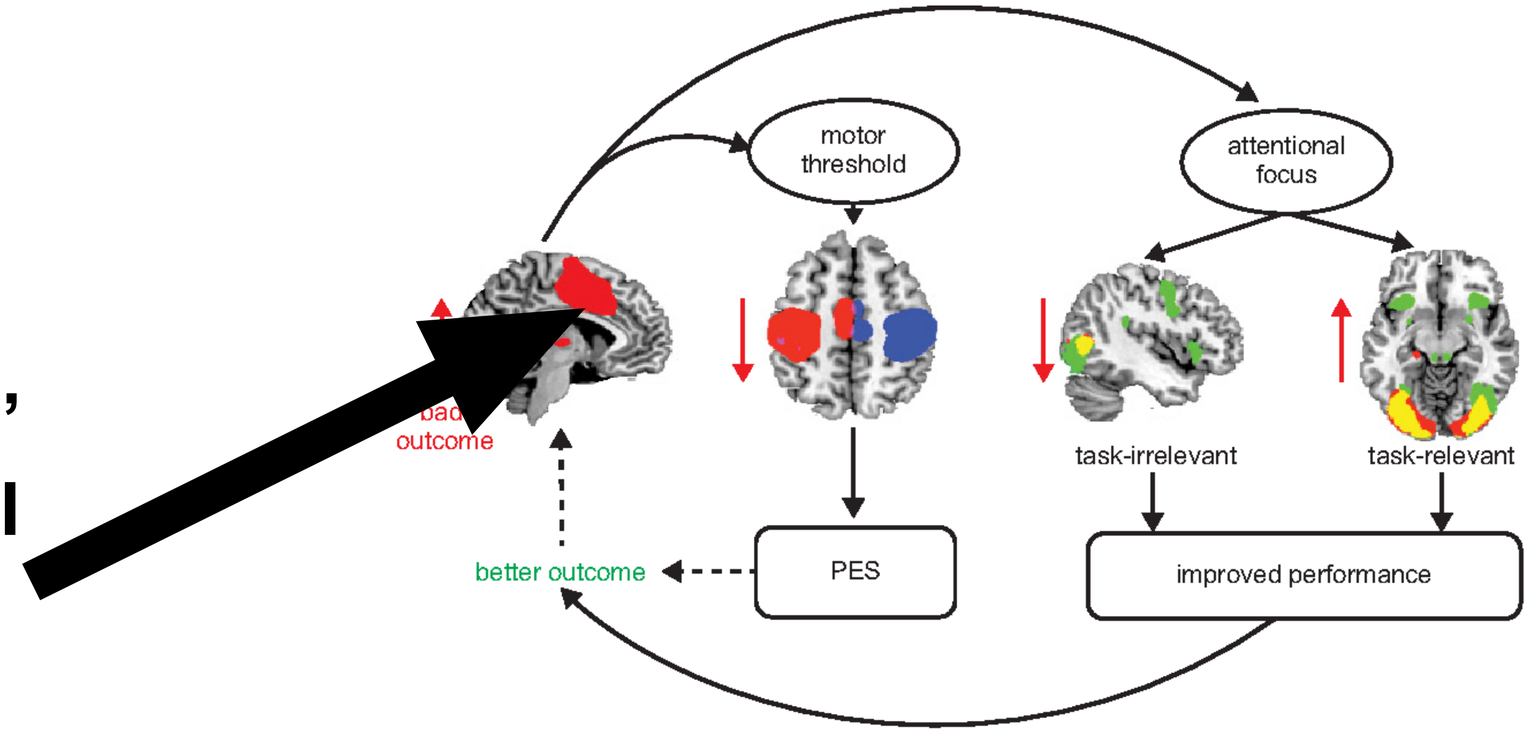


Ullsperger, Danielmeier, & Jocham, 2012

Error management

Thanks to the Anterior Cingulate Cortex (ACC)

“Plastic changes” across the school years



Ullsperger, Danielmeier, & Jocham, 2012

Pedagogy X Error management

Montessori (CHILD-centered) versus traditional (ADULT-driven)

- **No grades, no punishments, no rewards**
  → removal of *conditions of worth*
- **Judgement-free, self-corrective materials**
  → *unconditional positive regard*
- **Freedom + uninterrupted working hours**
  → autonomy support
- **Peer-to-peer learning**
  → growth through relationship

Error monitoring system

Error monitoring

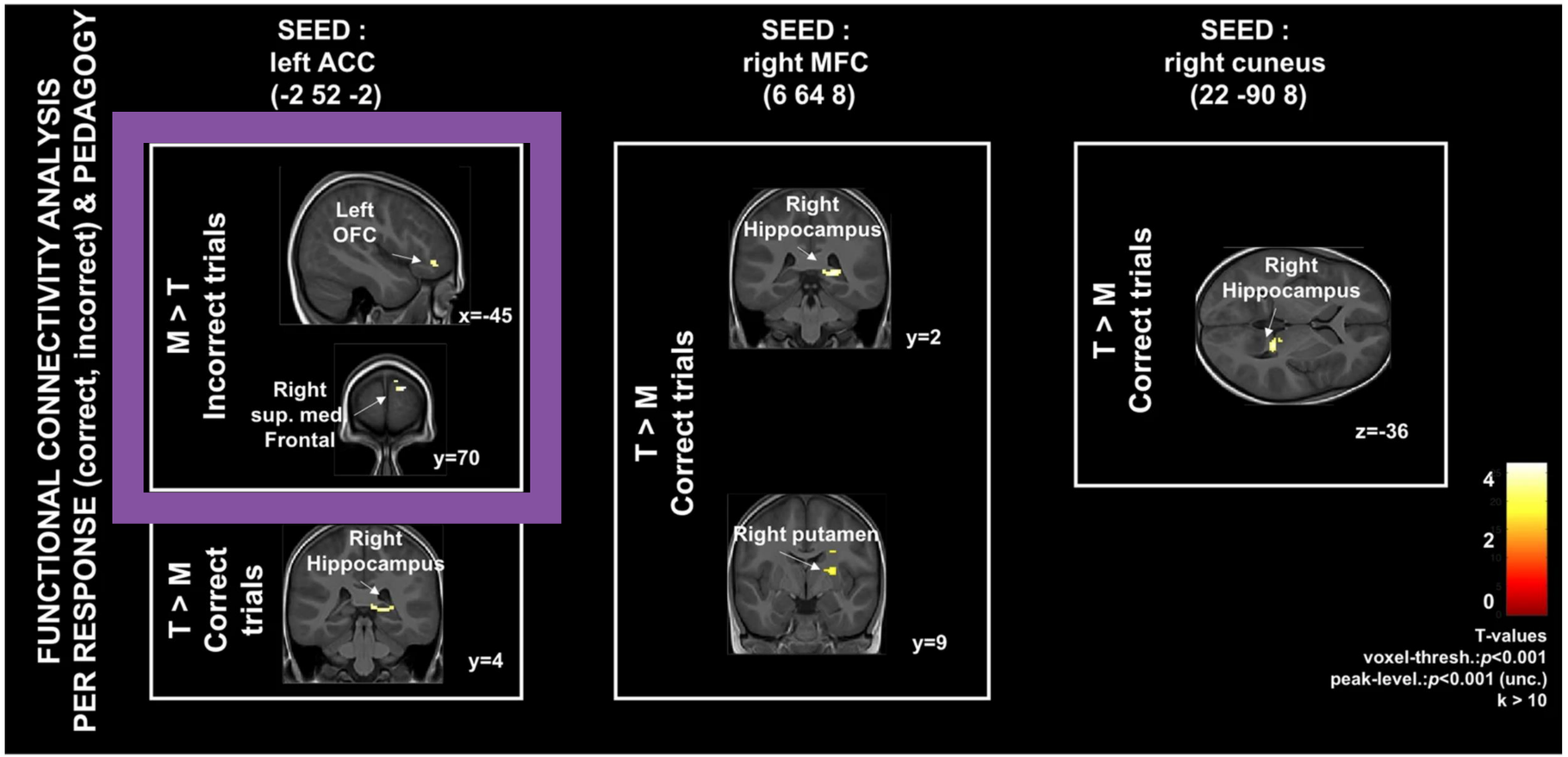
Detection of errors and self-correction

9 + 8 = 17

Denervaud, Knebel, Immordino-Yang, & Hagmann, 2019

Error monitoring

Detection of errors and self-correction

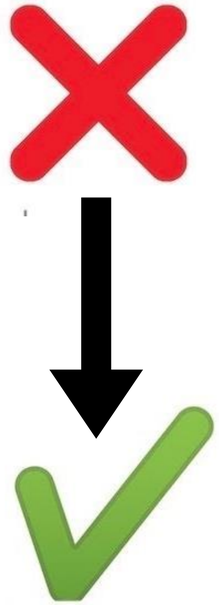


> Problem solving

Denervaud, Fornari, Yang, Hagmann, Immordino-Yang, & Sander, 2020

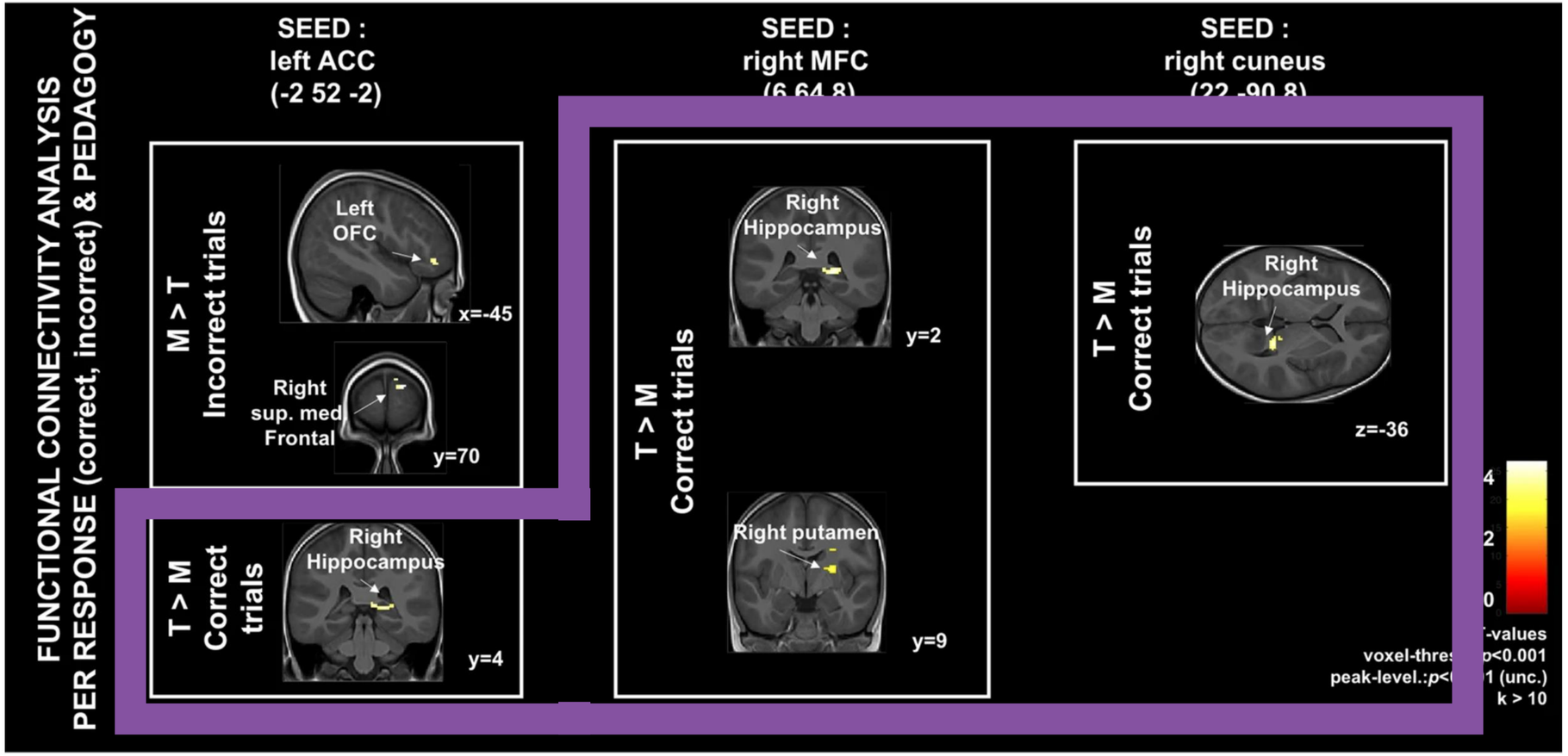
Error monitoring

Detection of errors and self-correction



Error monitoring

Detection of errors and self-correction

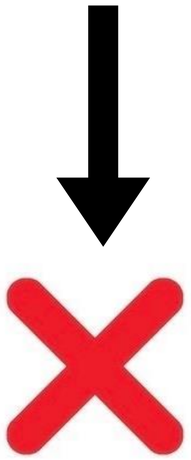


> Memorise good answers

Denervaud, Fornari, Yang, Hagmann, Immordino-Yang, & Sander, 2020

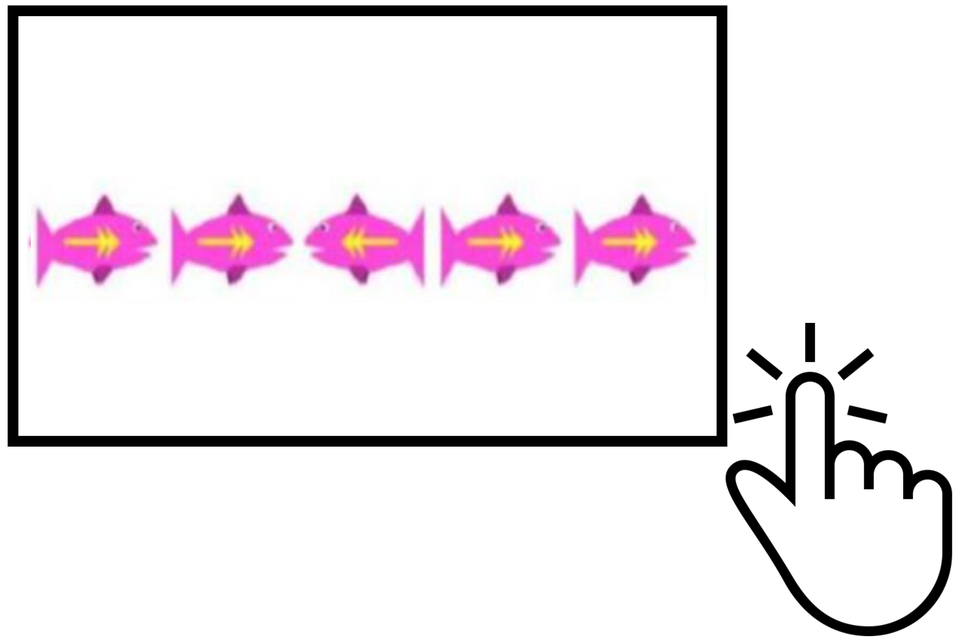
Error monitoring

Detection of errors and self-correction



Error monitoring — feedback integration

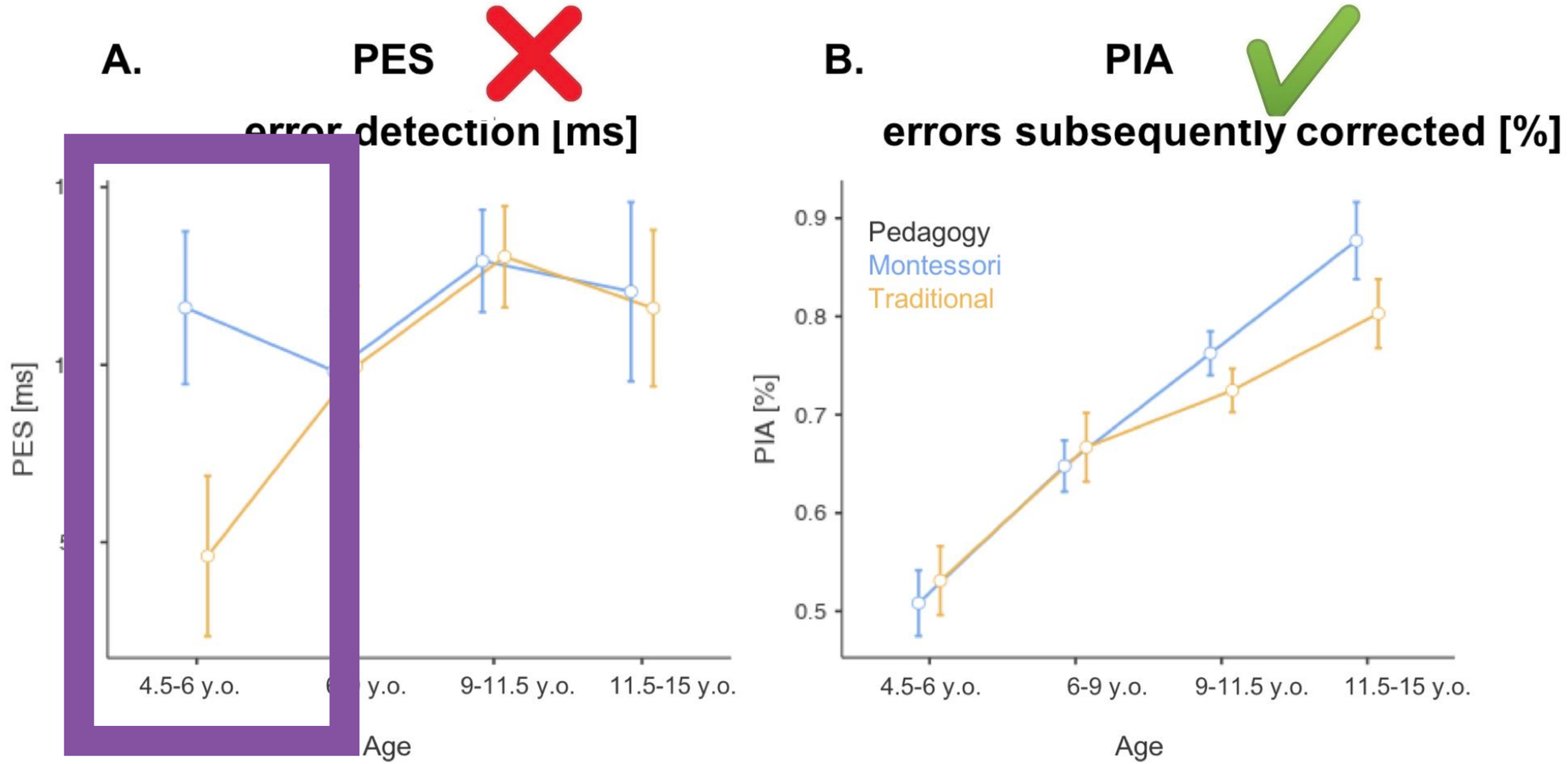
Detection of errors and self-correction



Denervaud, Knebel, Immordino-Yang, & Hagmann, 2019

Error monitoring — feedback integration

Detection of errors and self-correction



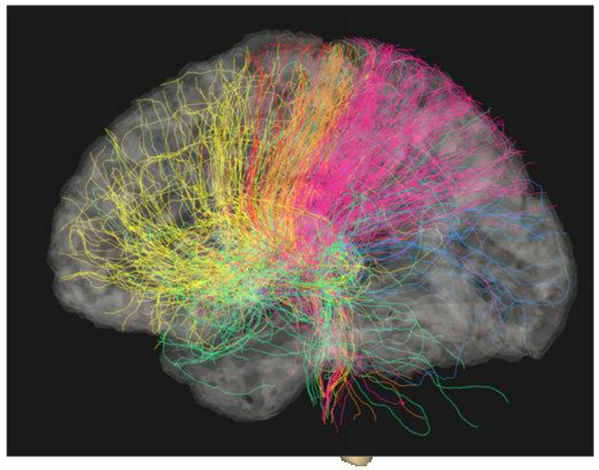
Denervaud, Knebel, Immordino-Yang, & Hagmann, 2019

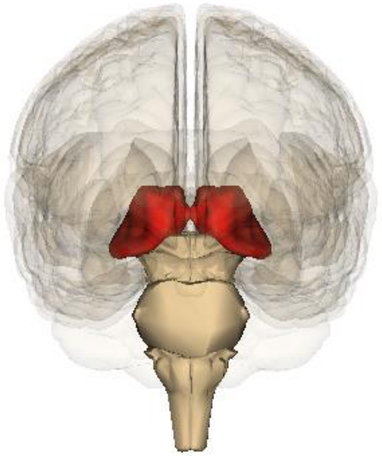
Error monitoring

Detection of errors and self-correction

Error monitoring — grounded cognition

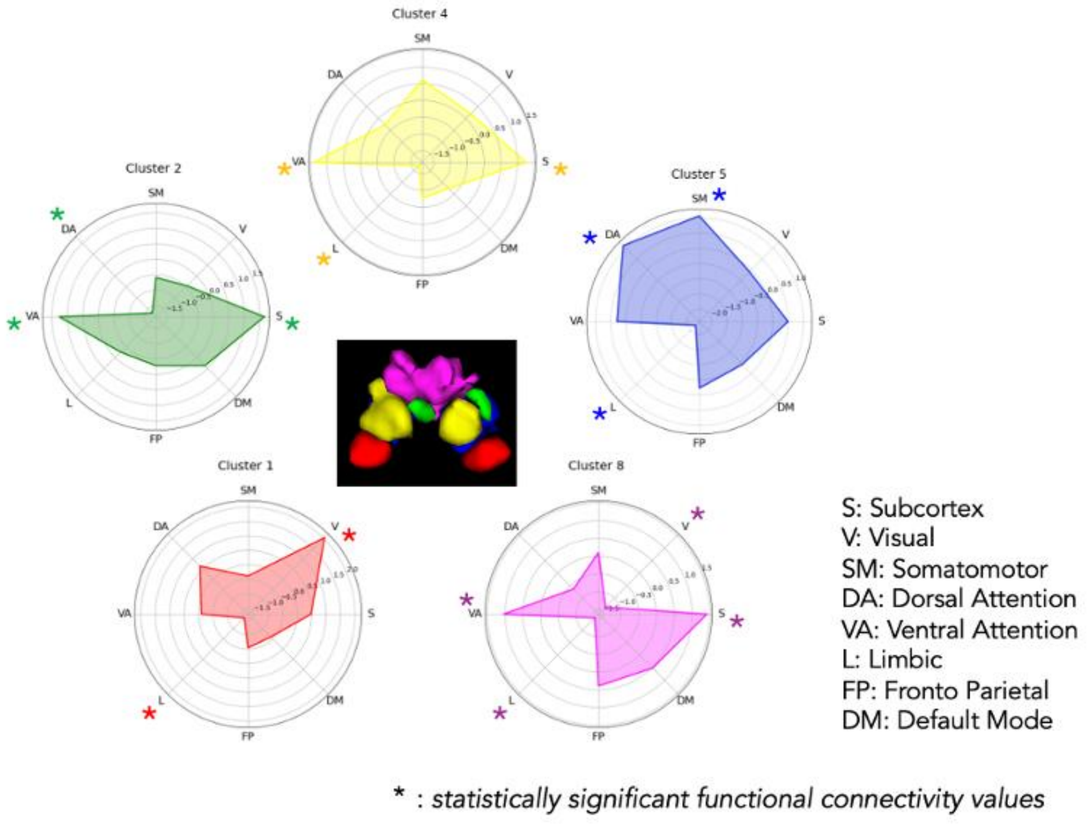
Detection of errors and self-correction





Error monitoring — grounded cognition

Detection of errors and self-correction



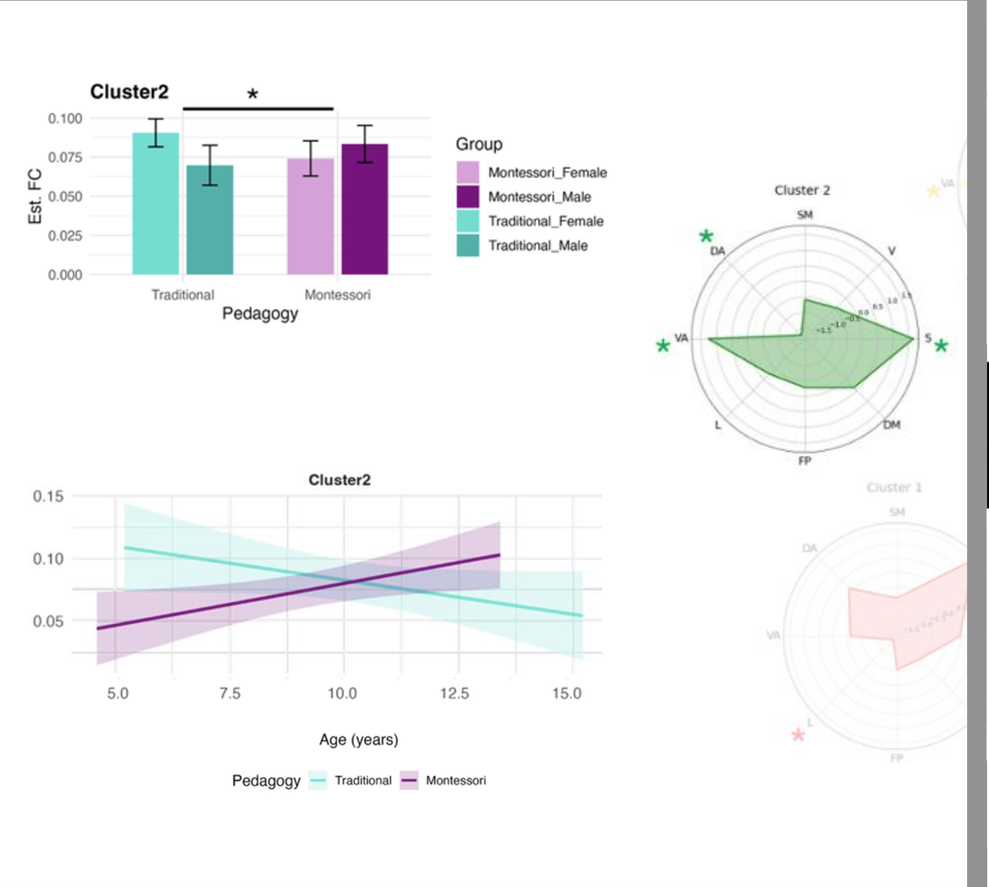


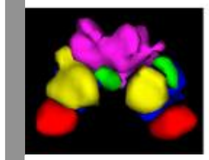


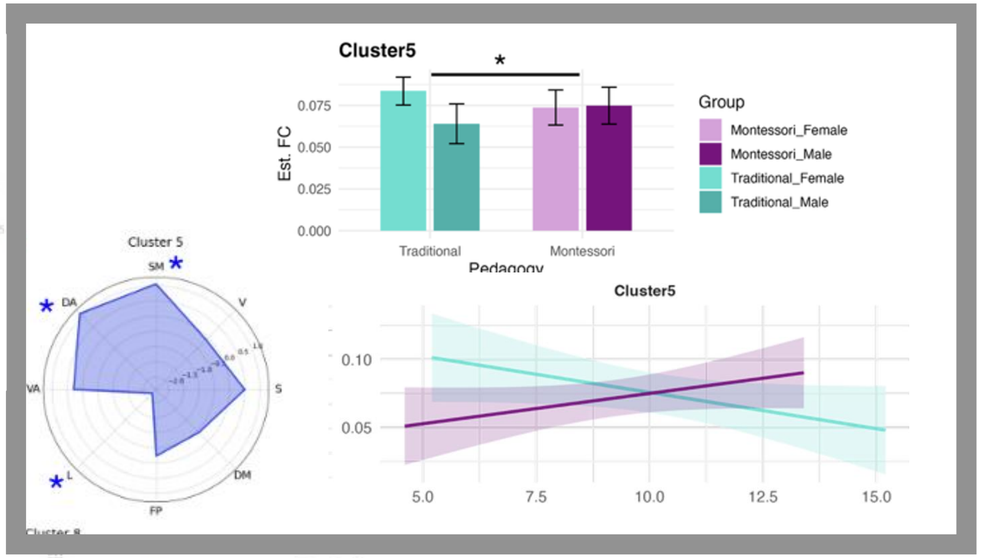

Mino-Matot*, Kebiri*, Jorge, Ledoux, Fornari, Bach Cuadra, & Denervaud, *Under Review*

Error monitoring — grounded cognition

Detection of errors and self-correction







S: Subcortex
V: Visual
SM: Somatomotor
DA: Dorsal Attention
VA: Ventral Attention
L: Limbic
FP: Fronto Parietal
DM: Default Mode

* : *statistically significant functional connectivity values*

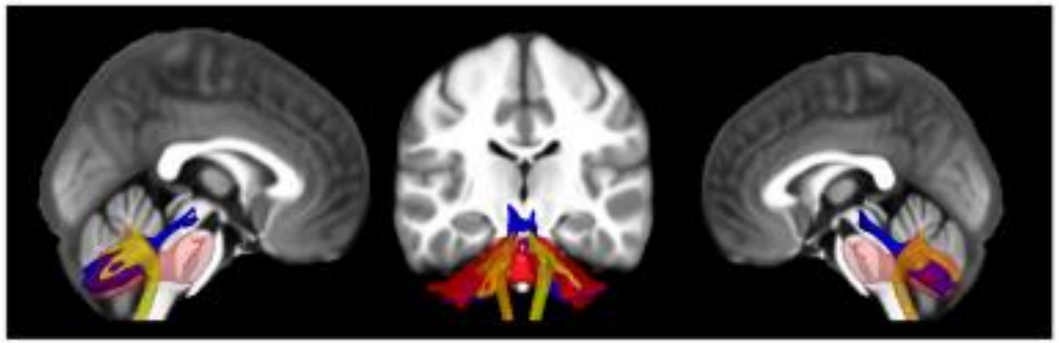





Mino-Matot*, Kebiri*, Jorge, Ledoux, Fornari, Bach Cuadra, & Denervaud, *Under Review*

Error monitoring — predictive cognition

Detection of errors and self-correction



Inferior Cerebellar Peduncle (Left, Right)

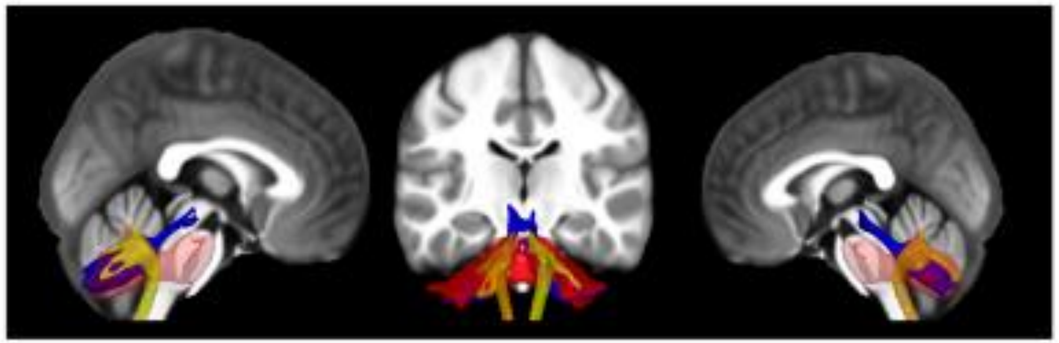
Middle Cerebellar Peduncle

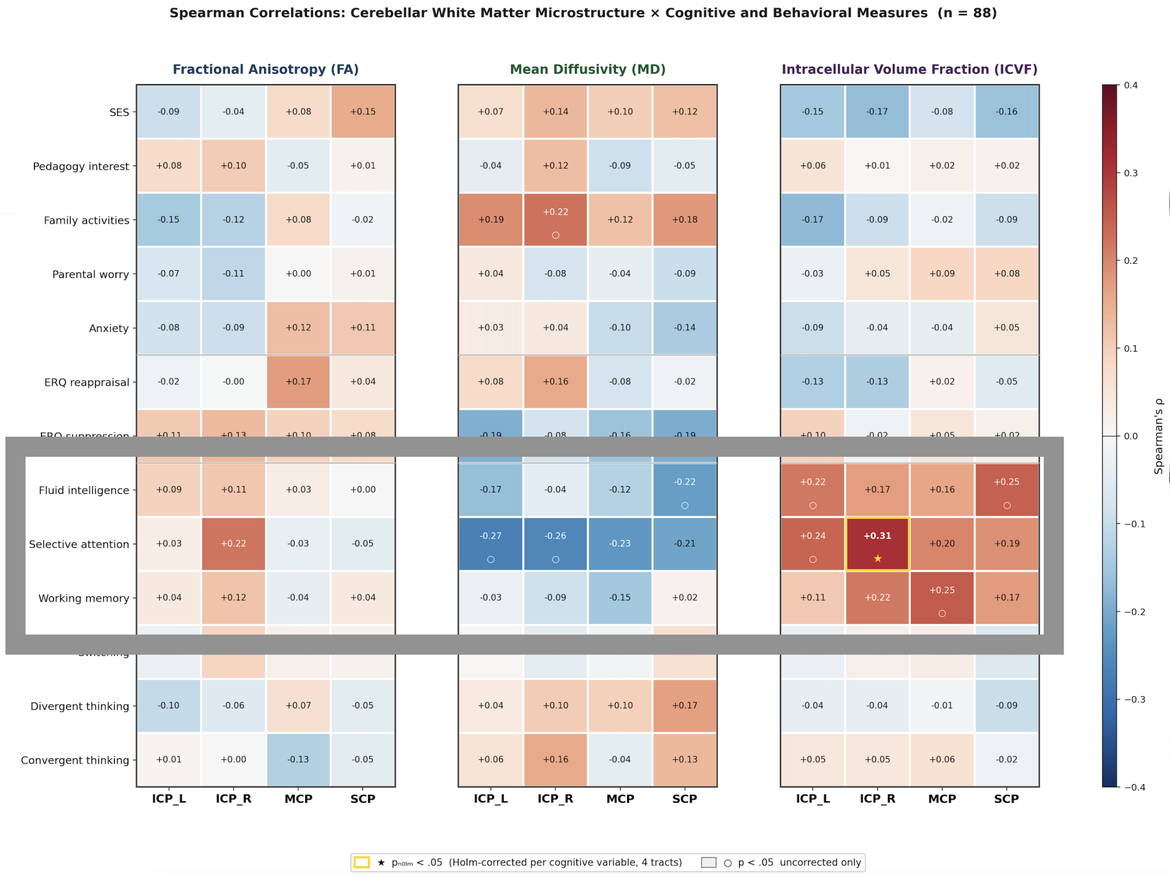
Superior Cerebellar Peduncle

Girard*, Gaujard*, Grosjean, Fischi-Gomez, & Denervaud, *In Revision*

Error monitoring — predictive cognition

Detection of errors and self-correction

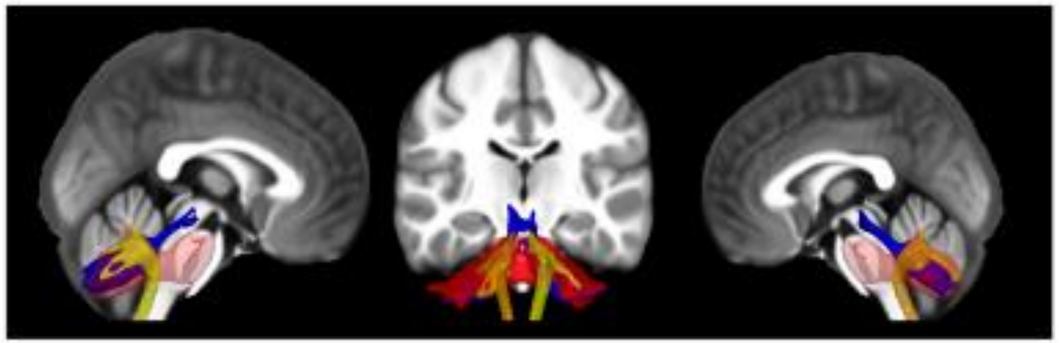


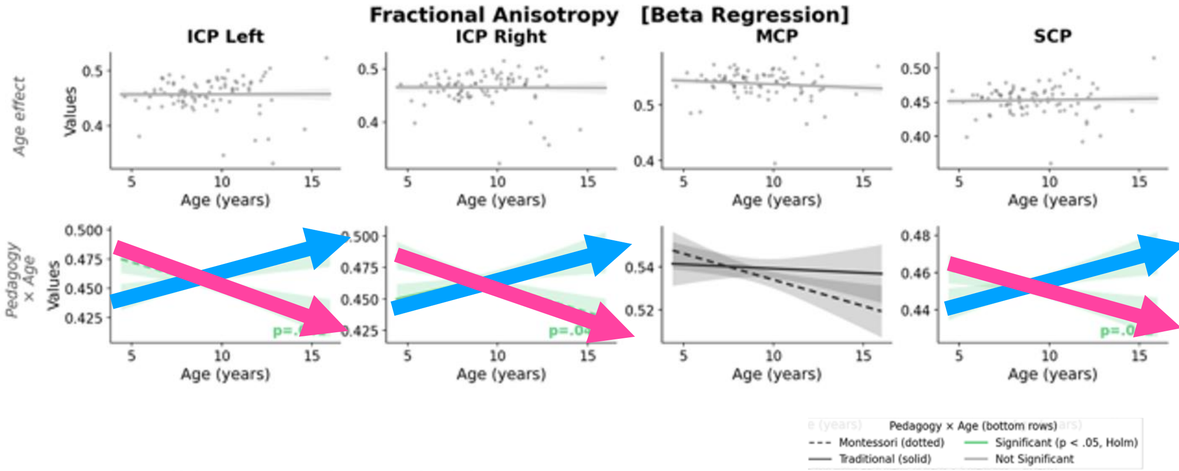


Girard*, Gaujard*, Grosjean, Fischi-Gomez, & Denervaud, *In Revision*

Error monitoring — predictive cognition

Detection of errors and self-correction



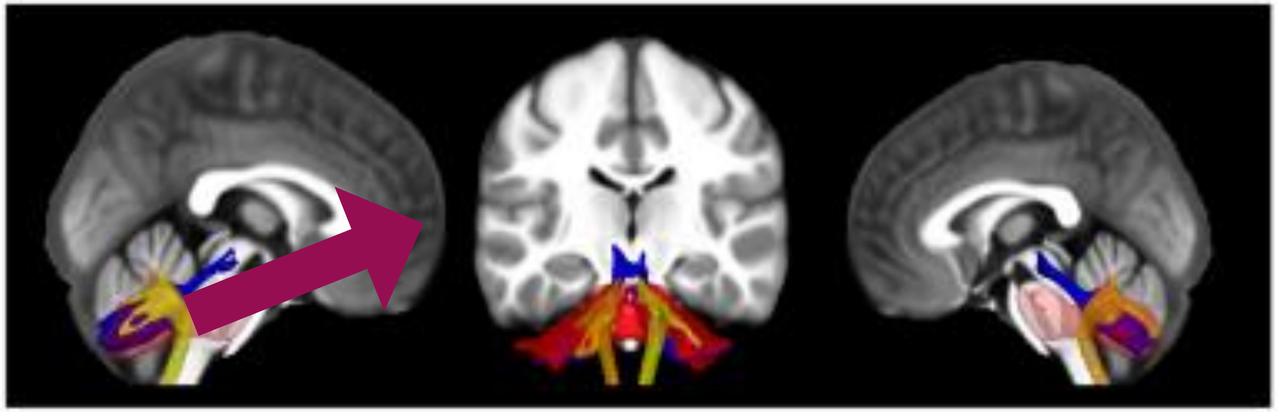


Traditionally-schooled children

Montessori-schooled children

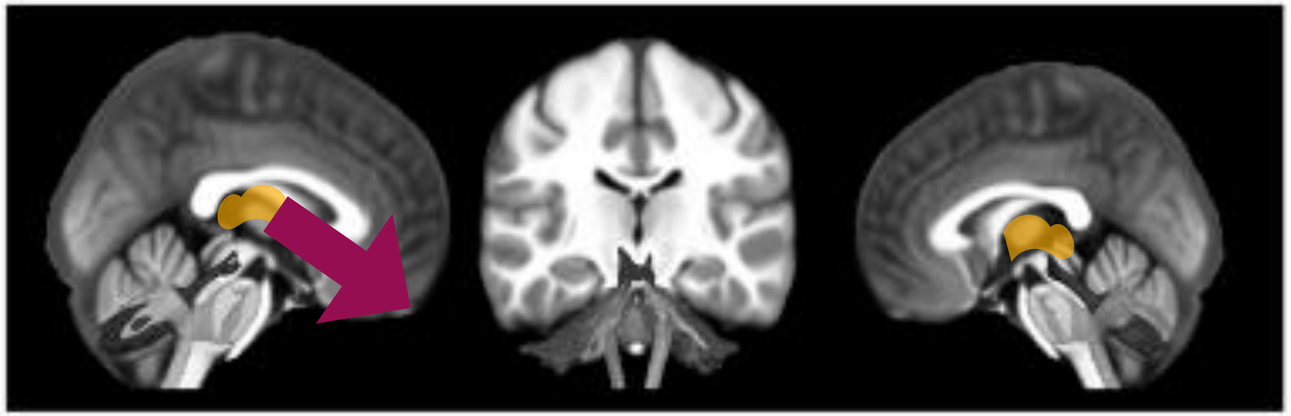
Girard*, Gaujard*, Grosjean, Fischi-Gomez, & Denervaud, *In Revision*

Error monitoring — control vs agency?



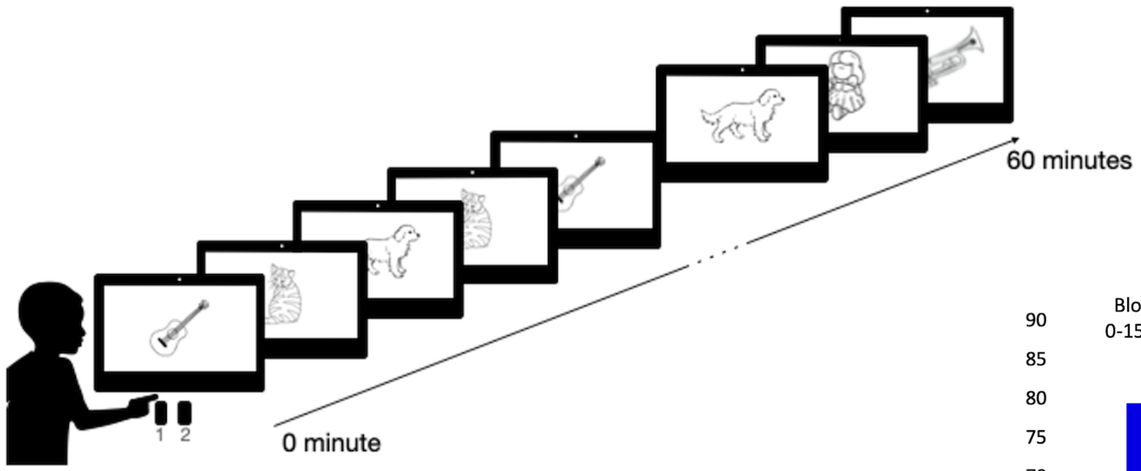
Prediction/anticipation

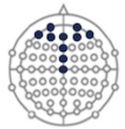
Agency/embodiment

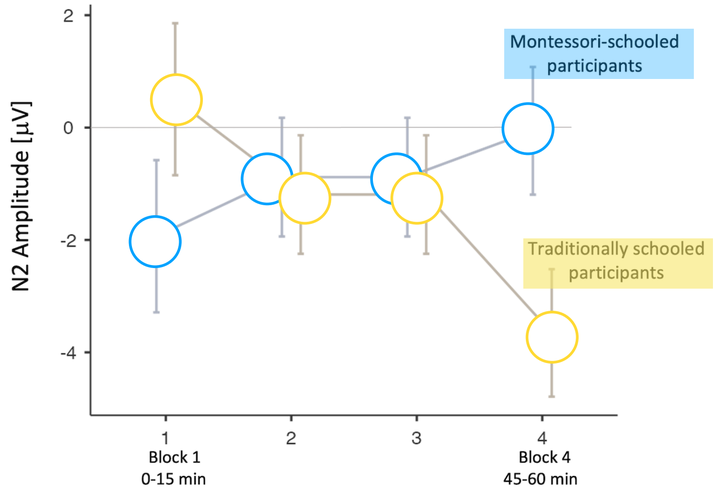


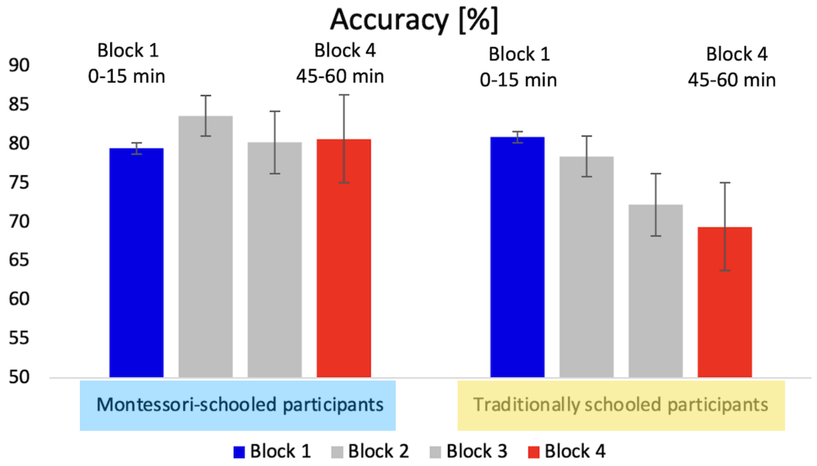
Error monitoring — attention

Detection of errors and self-correction





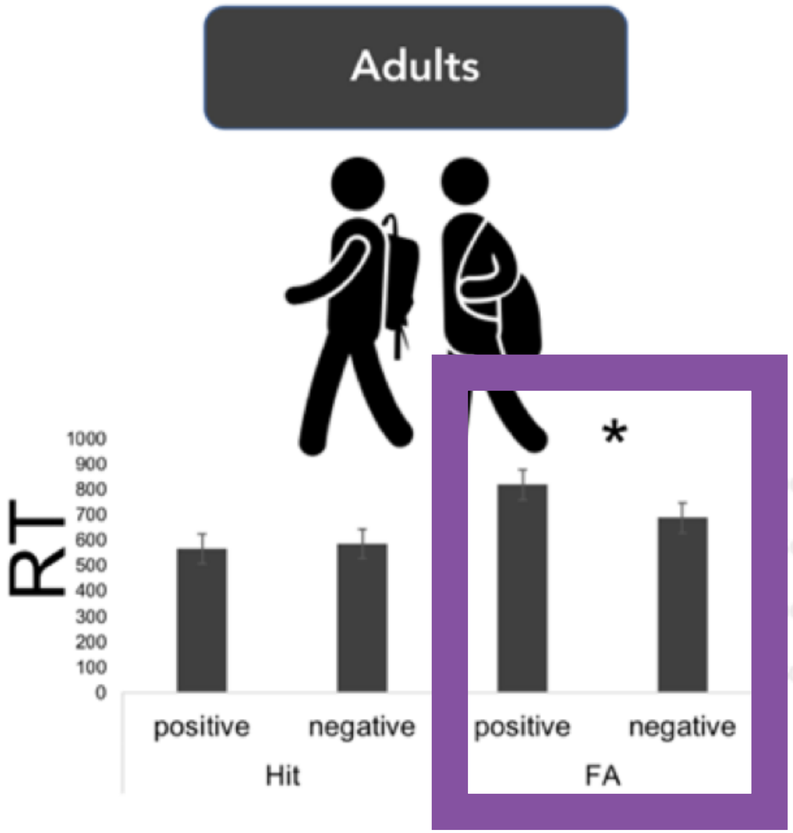




Aicoboaie*, Knebel*, Frick, Murray, & Denervaud, *In Review*

Error monitoring

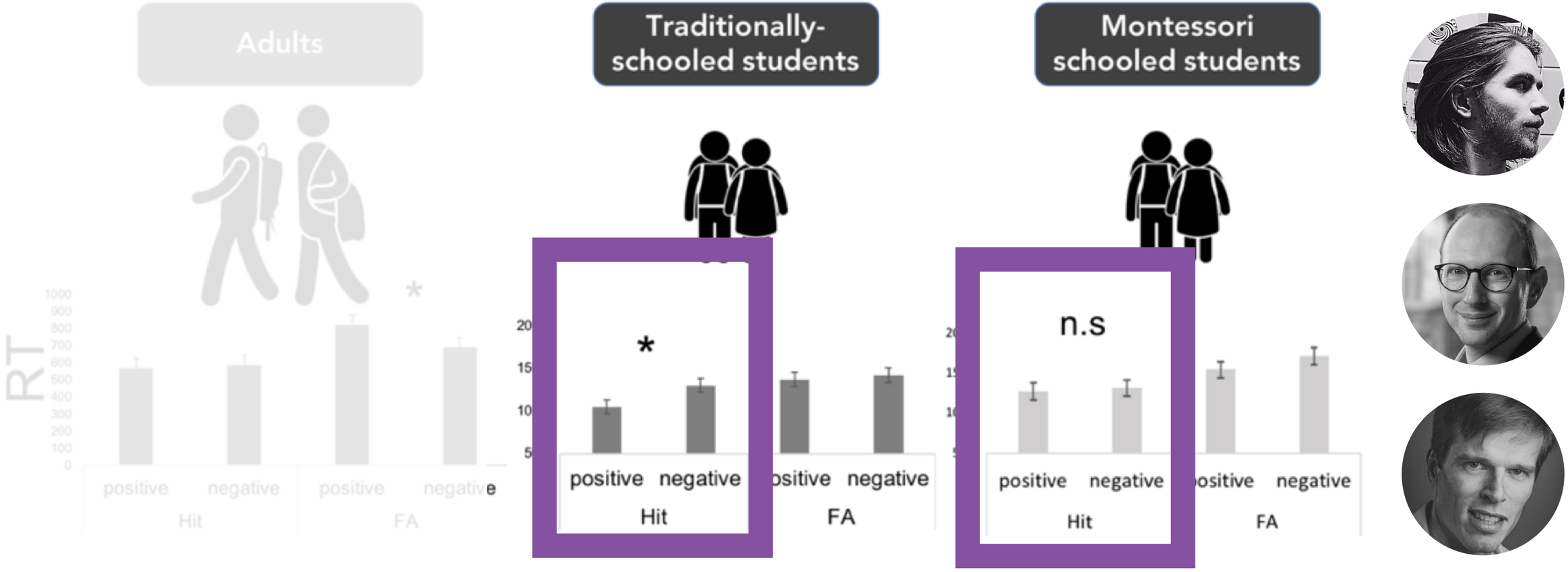
Affective (re)action



Denervaud, Hess, Sander, & Pourtois, 2020

Error monitoring

Affective (re)action



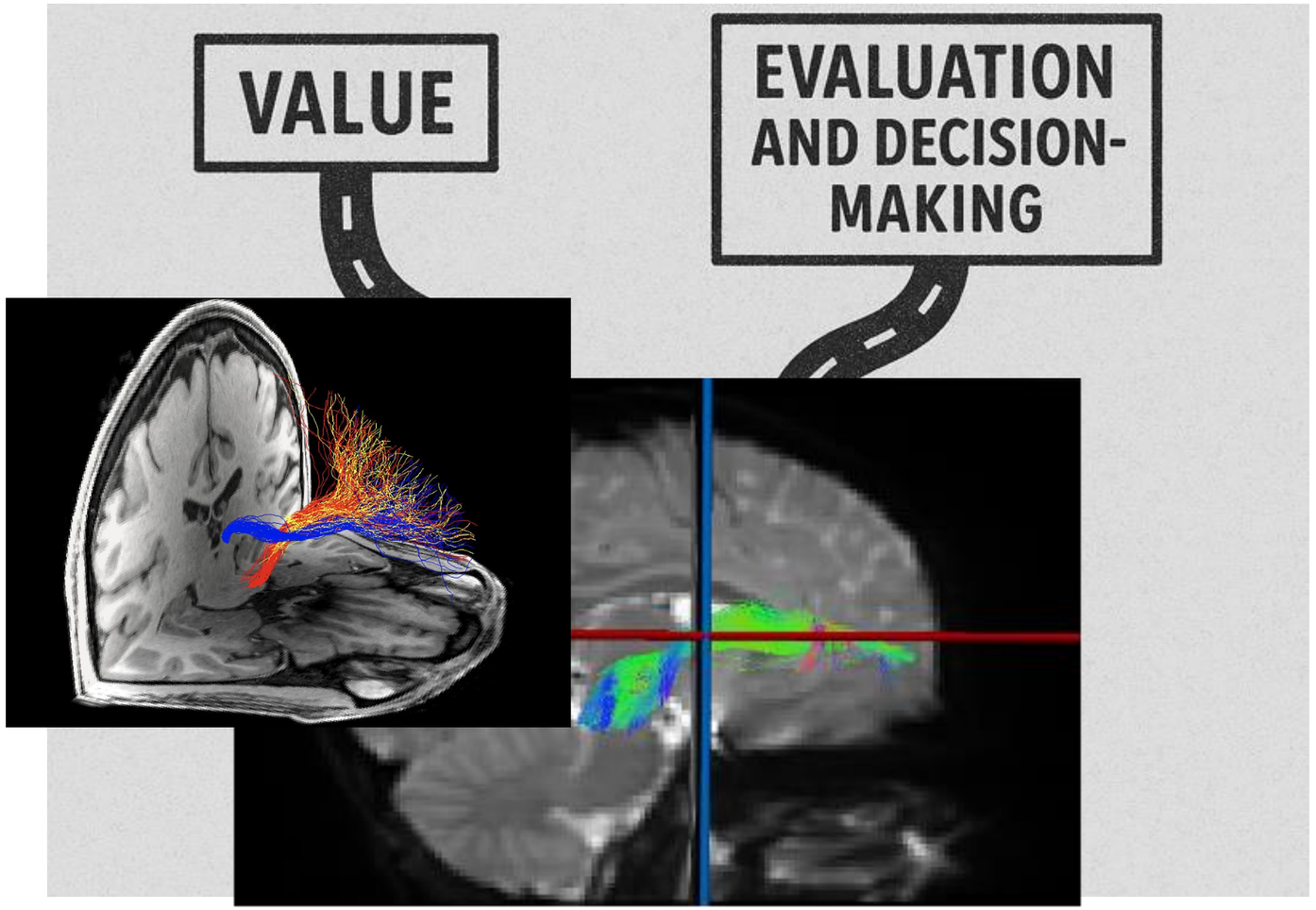
Denervaud, Hess, Sander, & Pourtois, 2020

Error monitoring

Affective (re)action

Error monitoring

Reward System





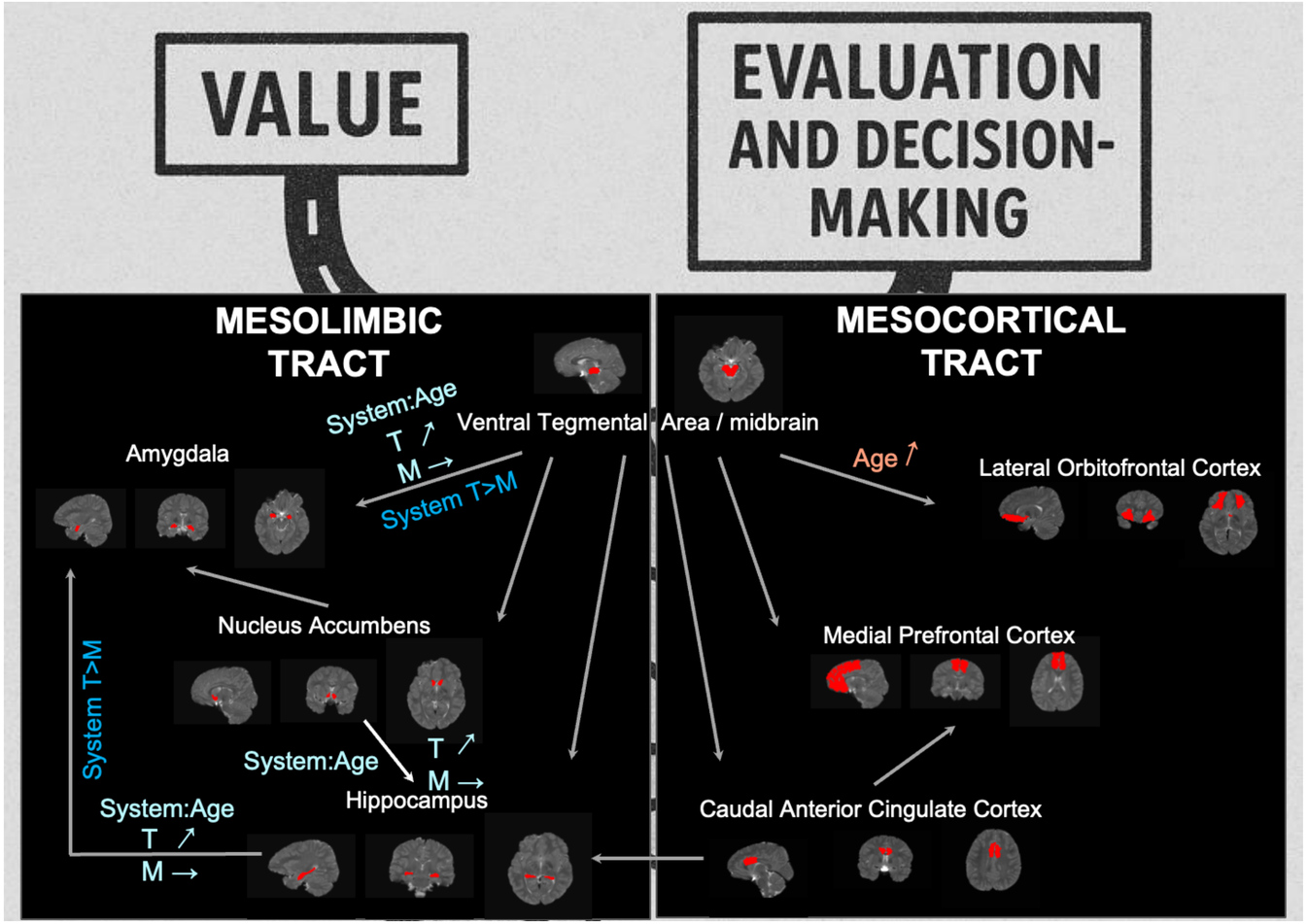




Girard*, Furrer*, Kabashi, Ledoux, Hagmann, Fischi Gomez, Bach Cuadra, & Denervaud, *Pending Submission*

Error monitoring

Reward System









Girard*, Furrer*, Kabashi, Ledoux, Hagmann, Fischi Gomez, Bach Cuadra, & Denervaud, *Pending Submission*

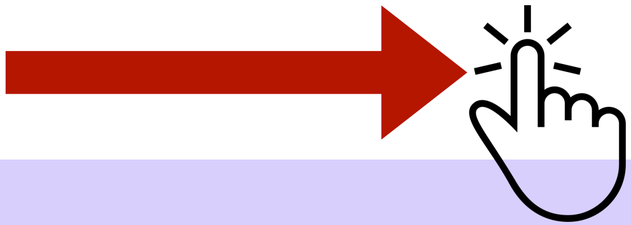
Error monitoring

Reward System

- Wonder and curiosity are present before any extrinsic reward.
- An actualising environment doesn't *create* motivation BUT it stops suppressing it.
- "Motivation as a process of actualisation": the drive is the organism's, not the reward schedule’s (INTRINSIC and not EXTRINSIC, cf: SDT)

Error monitoring

The ‘social’ dimension of error



Denervaud, Mumenthaler, Gentaz, & Sander, 2020

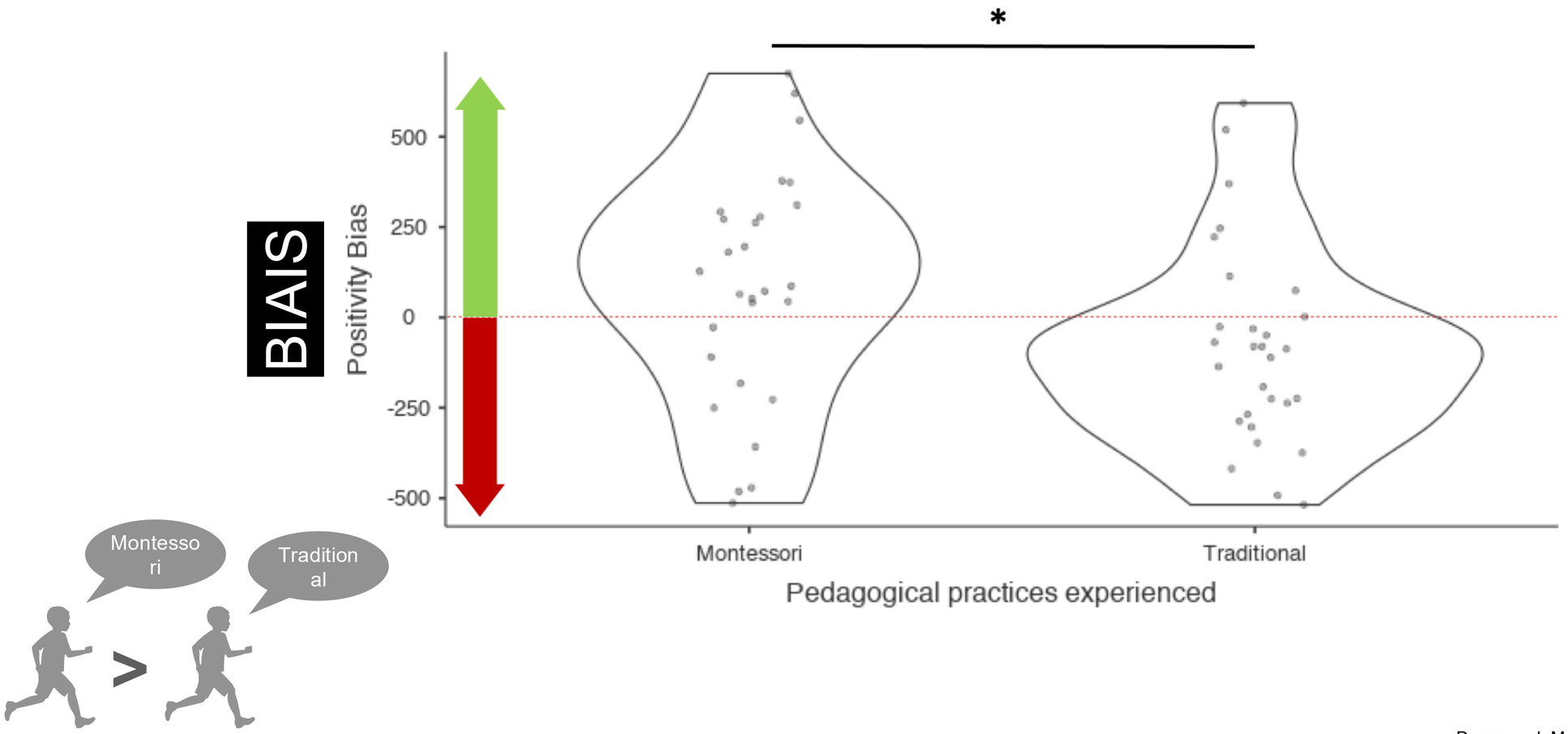
Error monitoring

The ‘social’ dimension of error

Denervaud, Mumenthaler, Gentaz, & Sander, 2020

Error monitoring

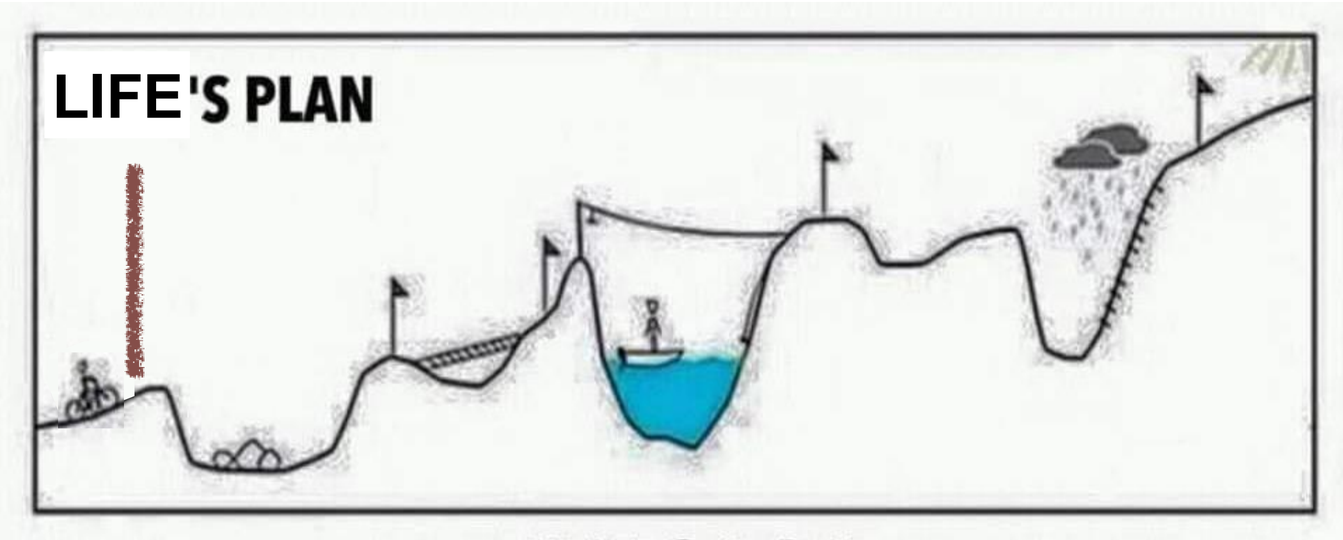
The ‘social’ dimension of error



Denervaud, Mumenthaler, Gentaz, & Sander, 2020

Learning to deal with ERRORS =

Training of flexibility and creativity (=generate and implement novelty)



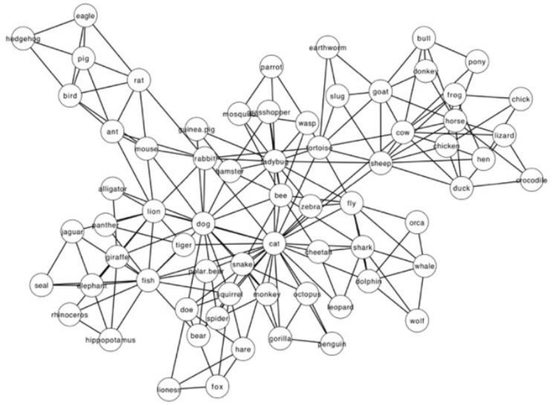
Memory X Pedagogy

Montessori versus traditional

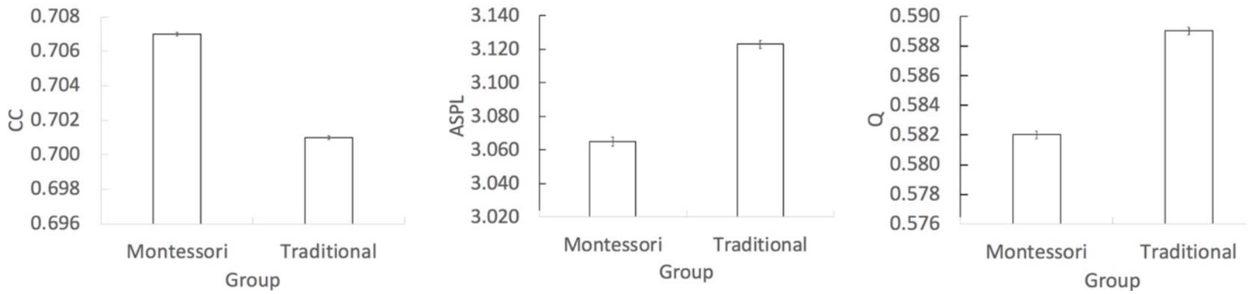
	Group				
	M	T	*t*-test or X^2	*p*-values	Cohen's d or Phi
Mean total number of responses	16.4 (5.0)	14.8 (5.8)	1.23	.225	0.30
Number of unique responses	37/105	19/87	5.16	.023	0.28
Creativity Divergent	9.6 (3.7)	7.1 (5.1)	2.34	.02	0.58
Creativity Convergent	5.3 (1.7)	2.6 (1.3)	7.10	< .001	1.74

Note. Mean and SD in parentheses.

Montessori



Traditional



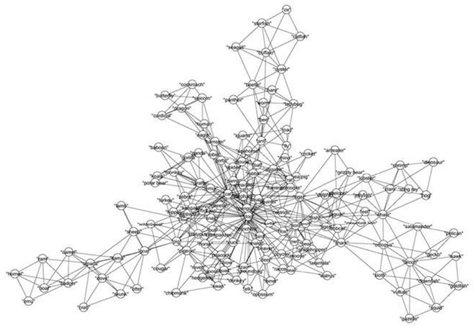
Note. Clustering coefficient (CC, left), average shortest path length (ASPL, center), and modularity (Q, right). X-axis : school group ; Y-axis : dependent variables (CC, ASPL, and Q; error bars denote standard error).

Denervaud, Christensen, Kenett, & Beaty, 2021

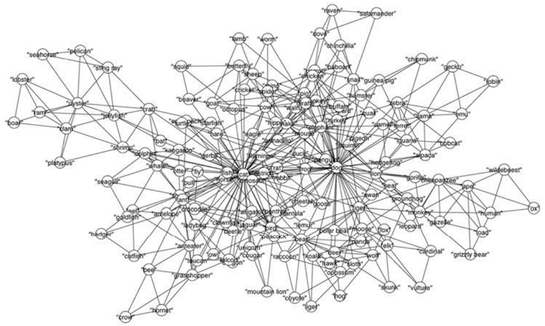
Semantic Network

In adults

Openess to new experience



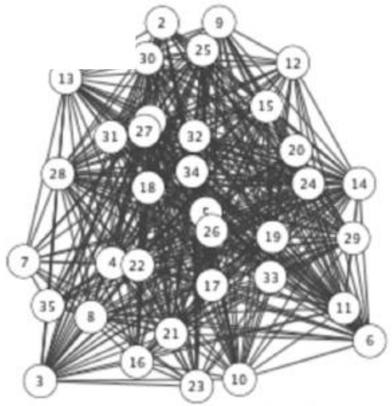
Low



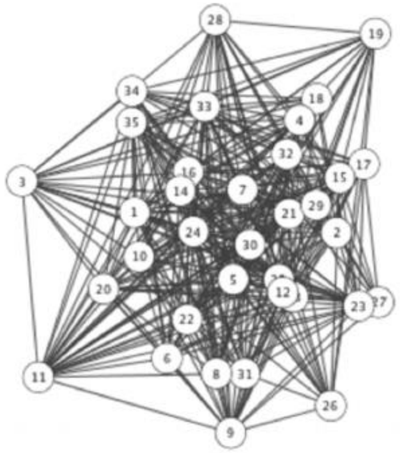
High

Christensen et al., 2018

Creative thinking



High creative

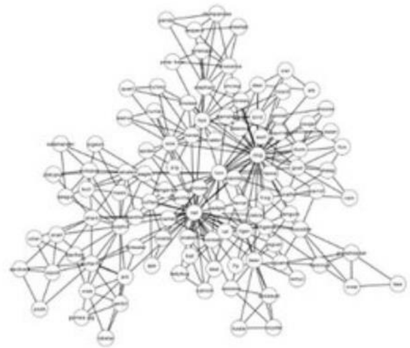


Low creative

Metaphore production

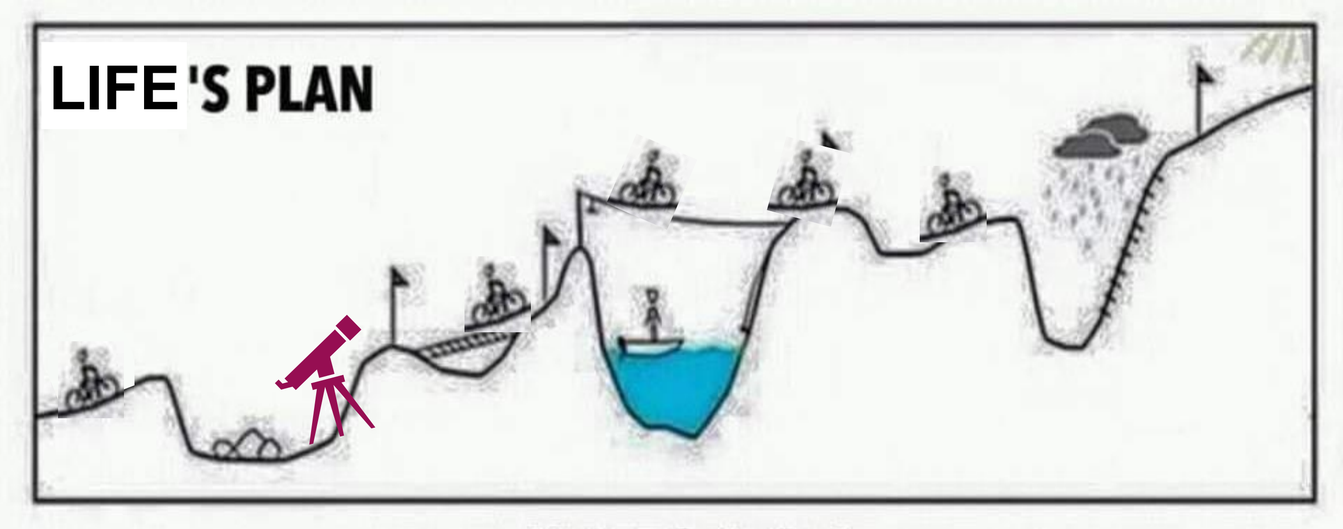
Low Creative
Metaphor Producers

High Creative
Metaphor Producers



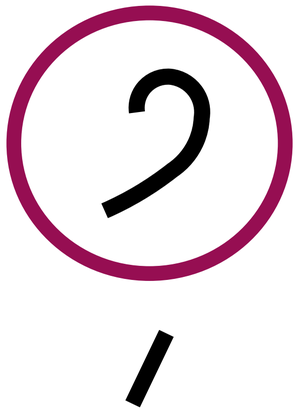
Li, Kenett, Hu, & Beaty, 2021

Peer-peer learning as an important learning factor ?



Learning from peers versus adults

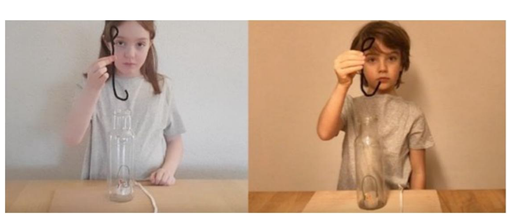
Critical thinking

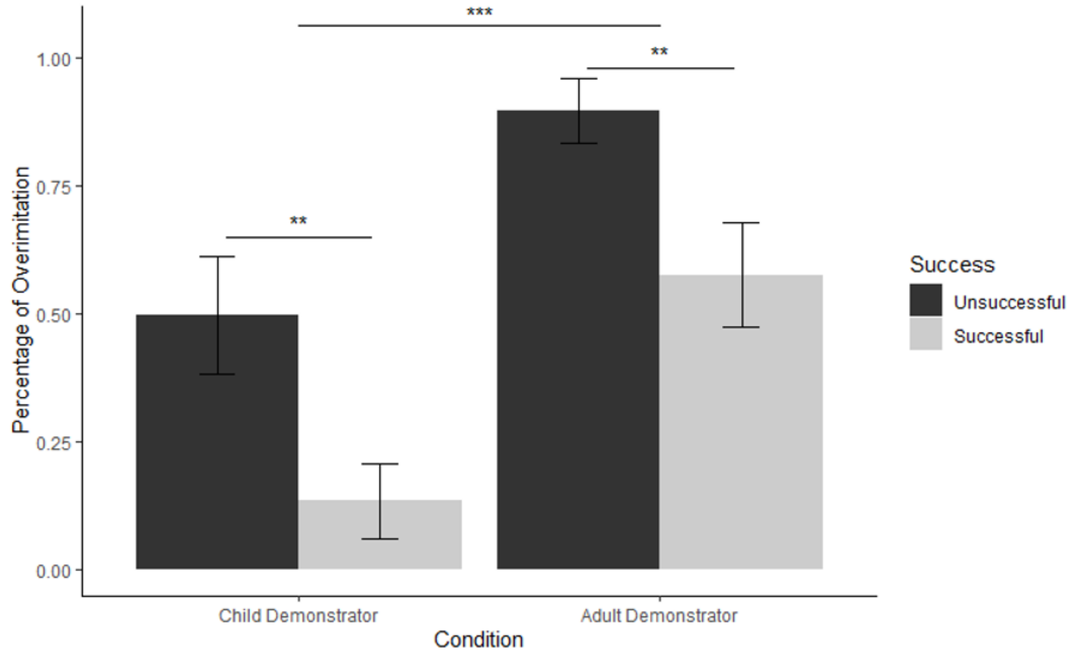


Décaillet, Frick, Lince, Gruber, & Denervaud, 2024

Learning from peers versus adults

Critical thinking

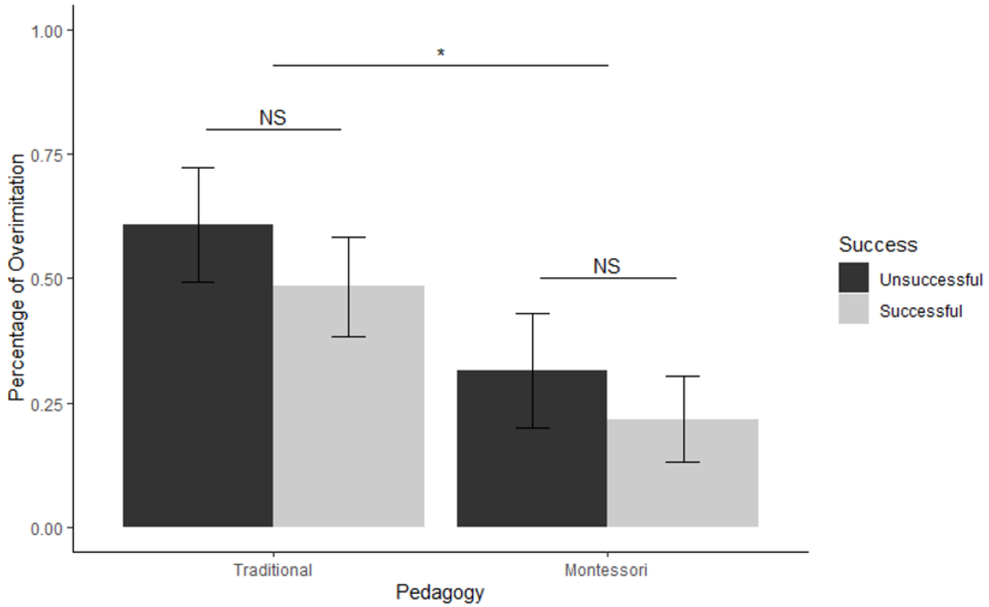




Décaillet, Frick, Lince, Gruber, & Denervaud, 2024

Flexible self-direction

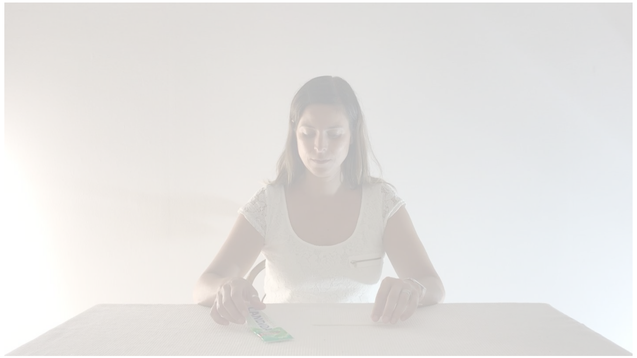
Learning from peers versus adults: critical thinking



Décaillet, Frick, Lince, Gruber, & Denervaud, *Under Review*

Learning from peers versus adults

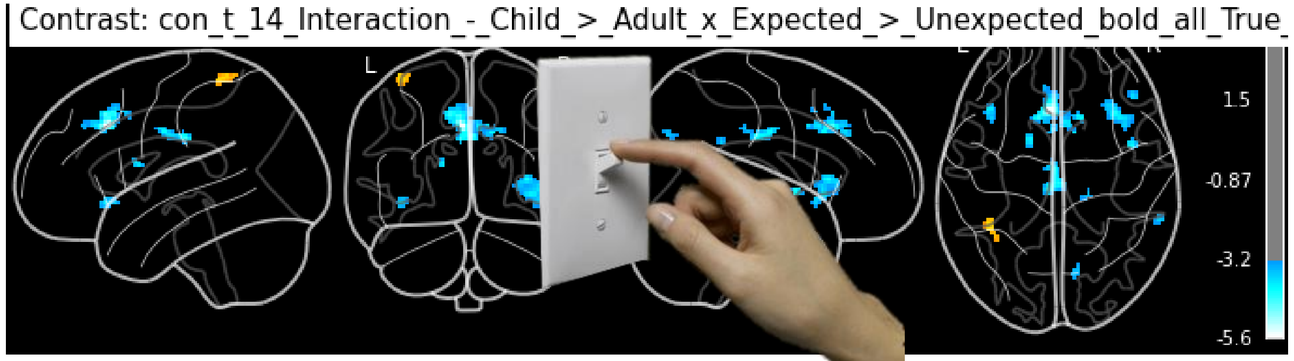
More salient?



Chiron*, Notter*, Eon Duval, Décaillet, Fornari, Beaty, & Denervaud, *In prep*

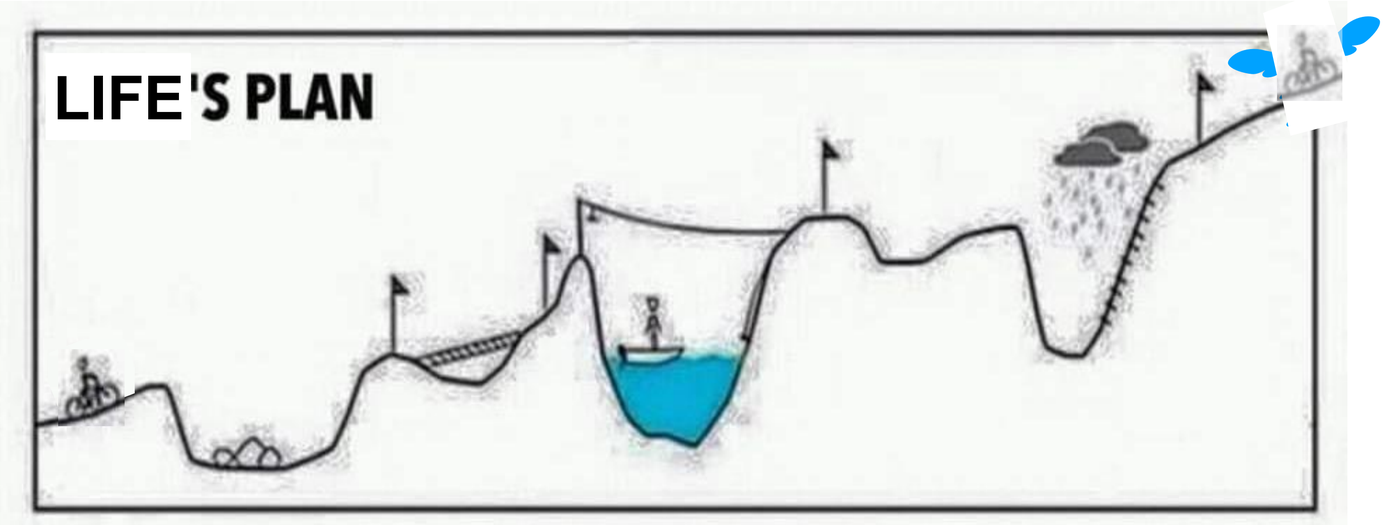
Learning from peers versus adults

More salient?



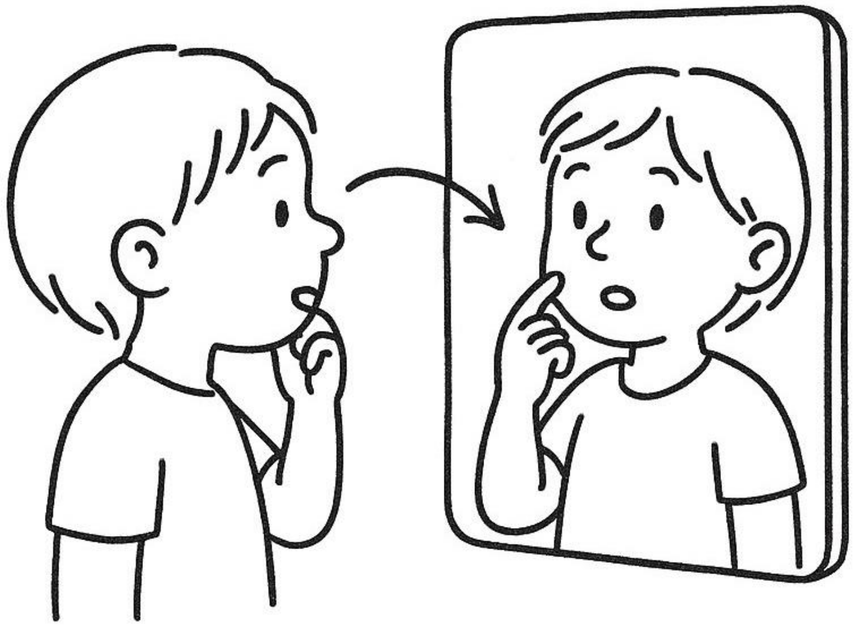
N=20 children aged 6 through 12, and N=22 adults aged > 21

Chiron*, Notter*, Eon Duval, Décaillet, Fornari, Beaty, & Denervaud, *In prep*



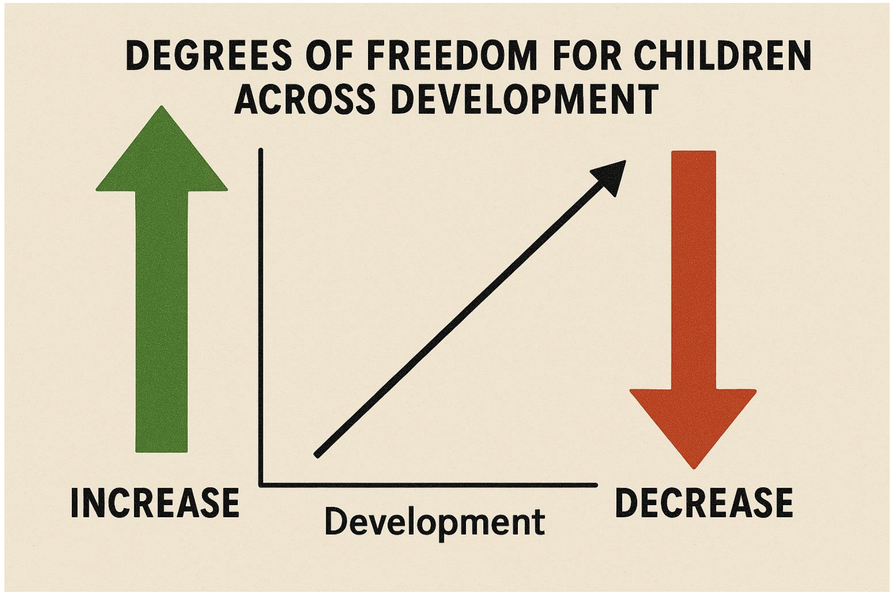
Error monitoring > Creativity and flexible self-direction >
Critical thinking in peer contexts > AUTONOMY & higher awareness ?

Adapted environments - awareness



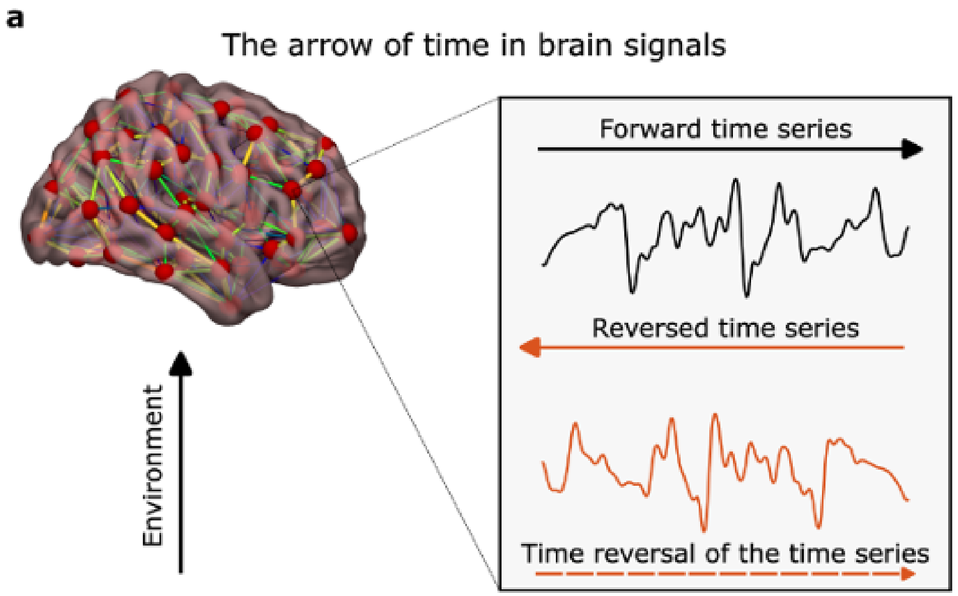
Adapted environments - awareness

Montessori



Traditional

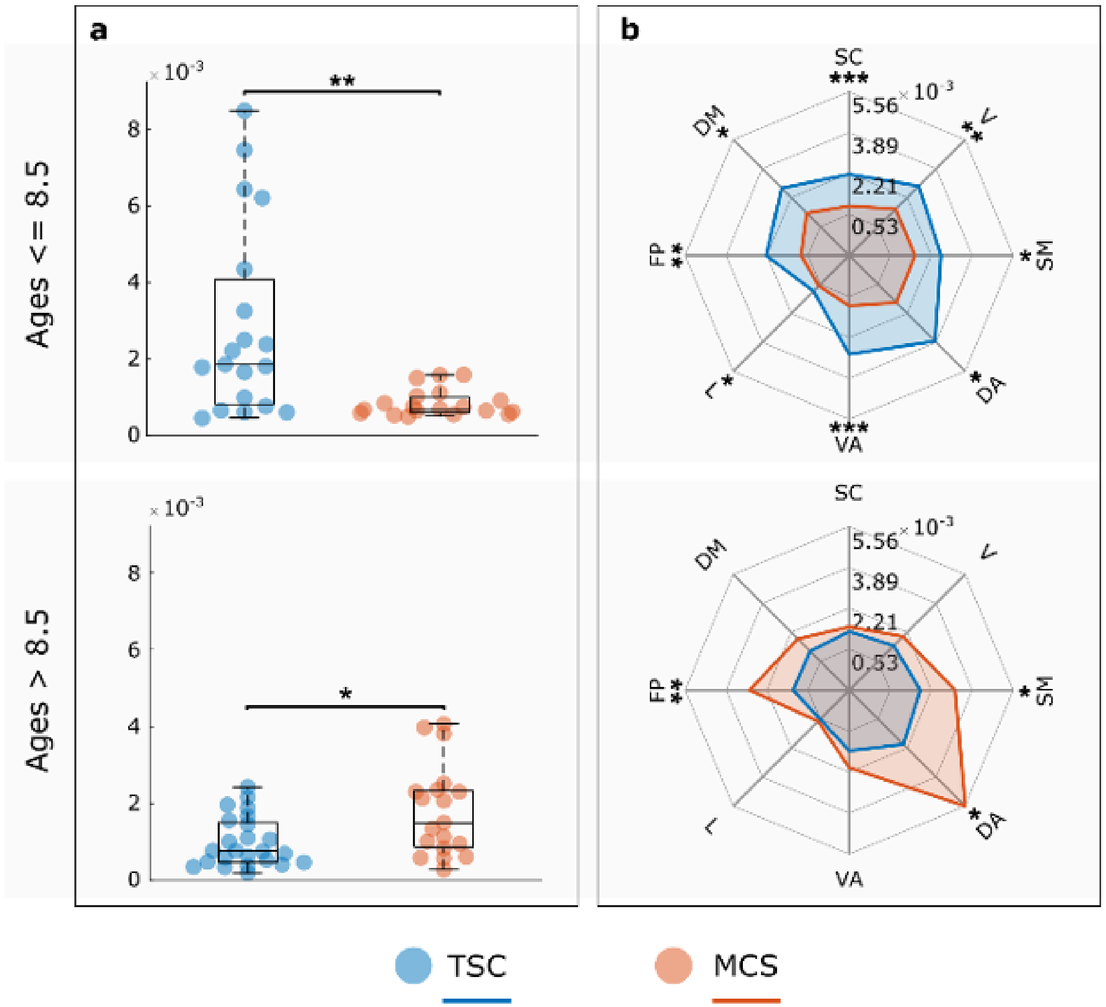
Higher awareness ?

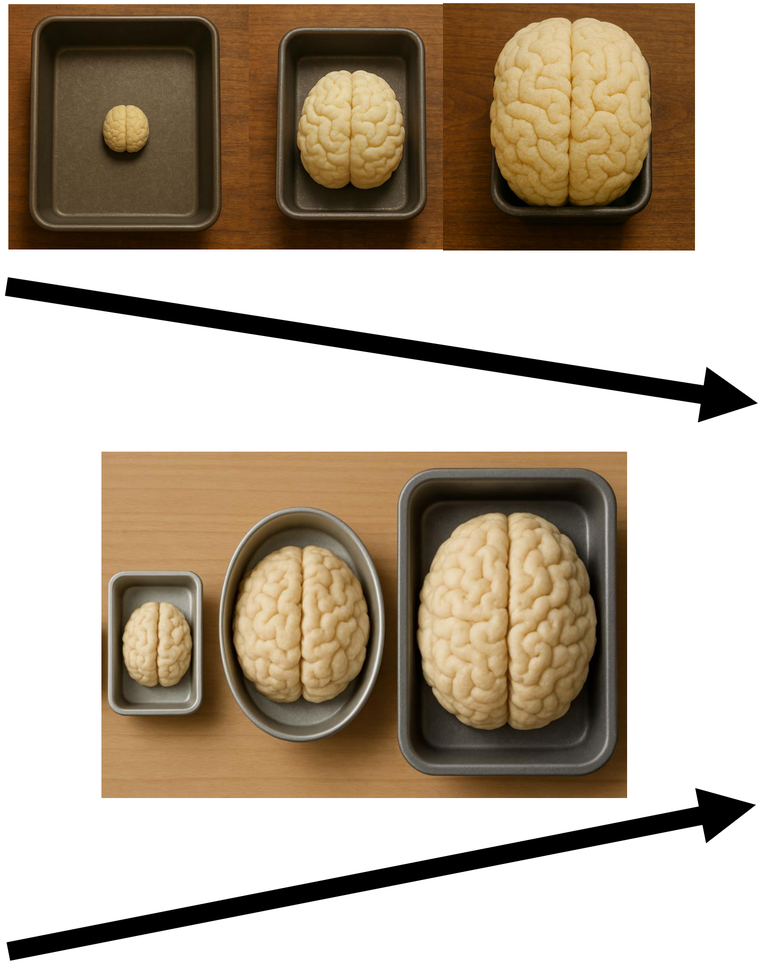


thermodynamics-inspired measure of neural complexity called ‘non-reversibility,’ associated with cognitive engagement and conscious awareness.

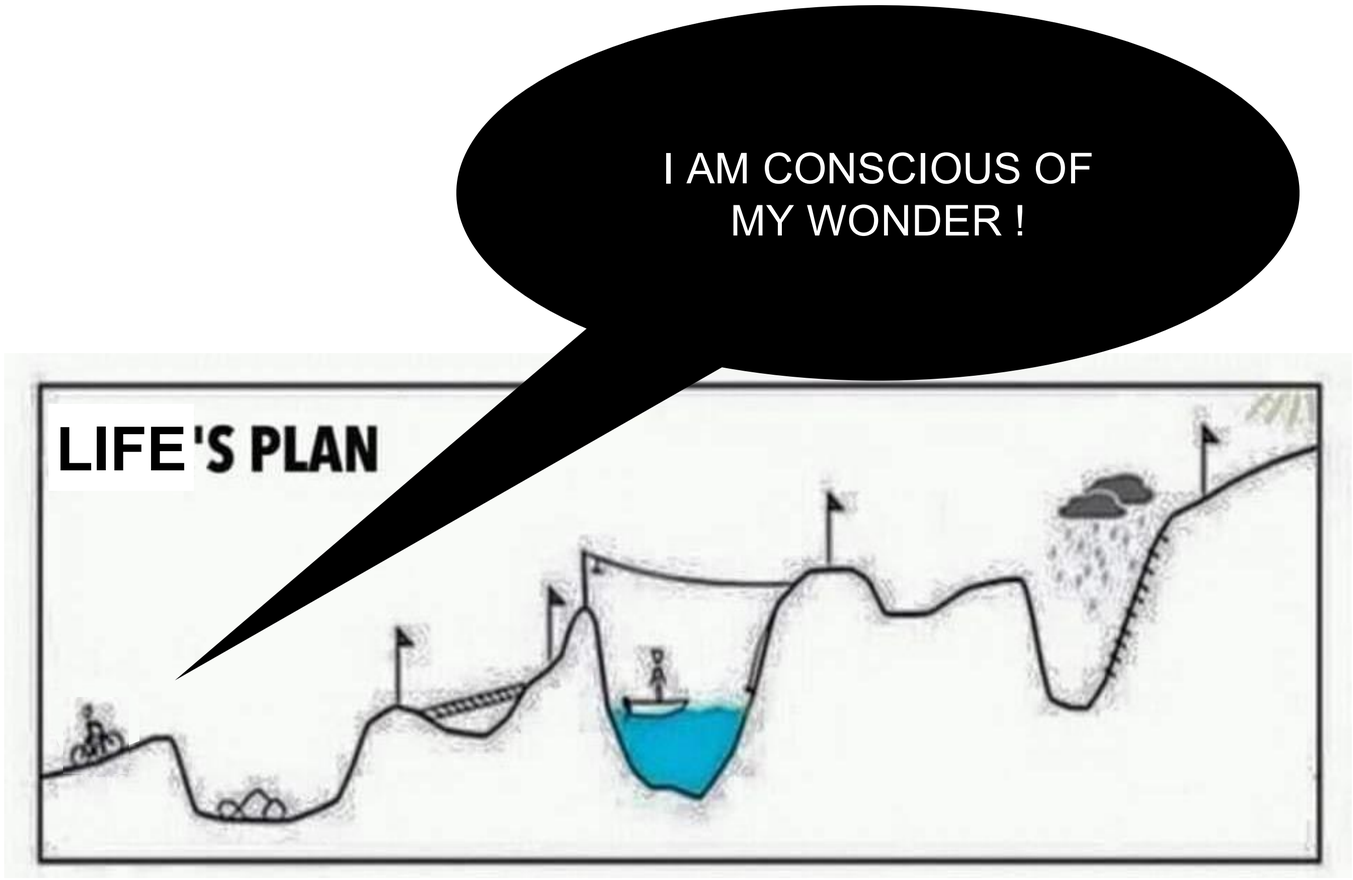
del Agua Banyeres, Escrichs, Sanz Perl, Kringelbach, Diamond, Denervaud* & Deco*, 2026

Higher awareness ?





del Agua Banyeres, Escrichs, Sanz Perl, Kringelbach, Diamond, Denervaud*[&] Deco*, 2026

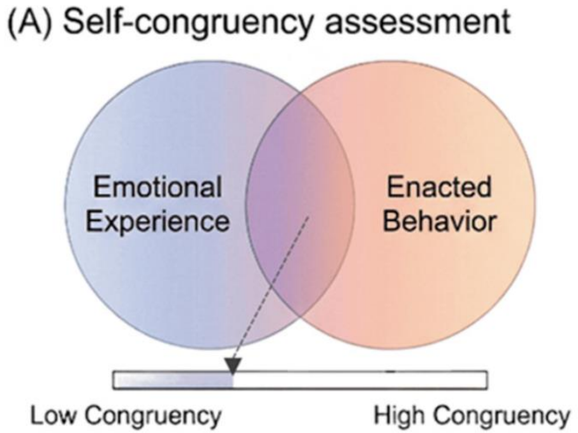


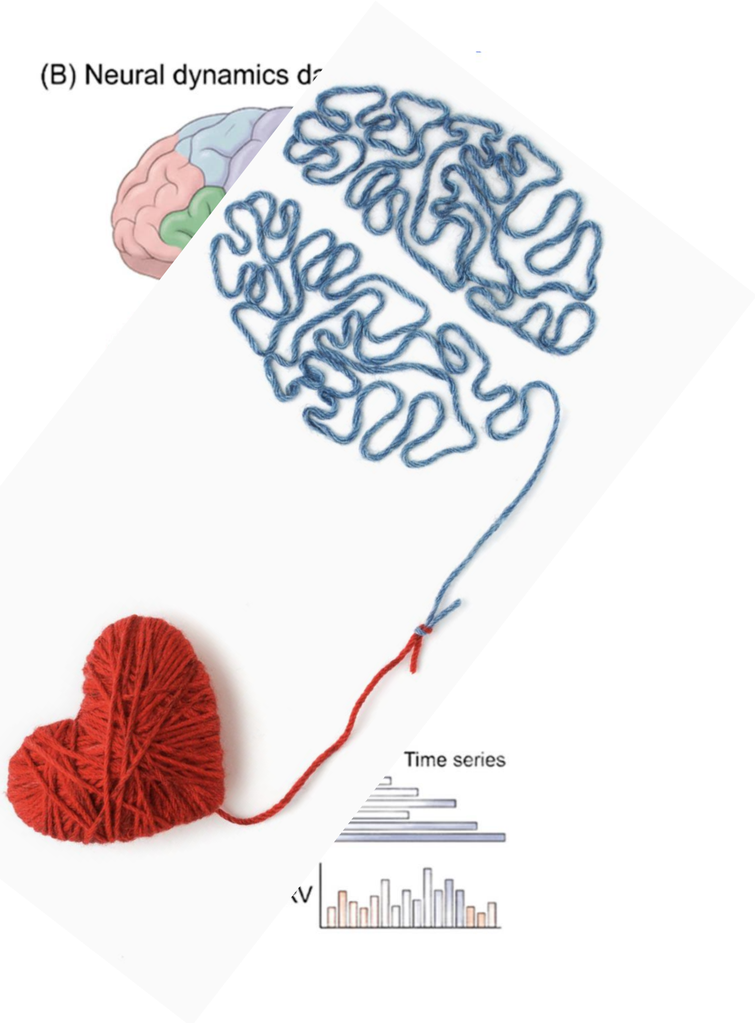
Rogers' *fully functioning person* ?
Adaptability may be the *actualising tendency* operating over time

Why actualization could be a unifying account ?

1	**Biology**	A self-maintaining organism with an intrinsic drive toward growth and complexity.
2	**Neuroscience**	Error-monitoring and reward circuits that turn experience into self-directed change
3	**Education**	Environments that either free the tendency or suppress it with extrinsic control.

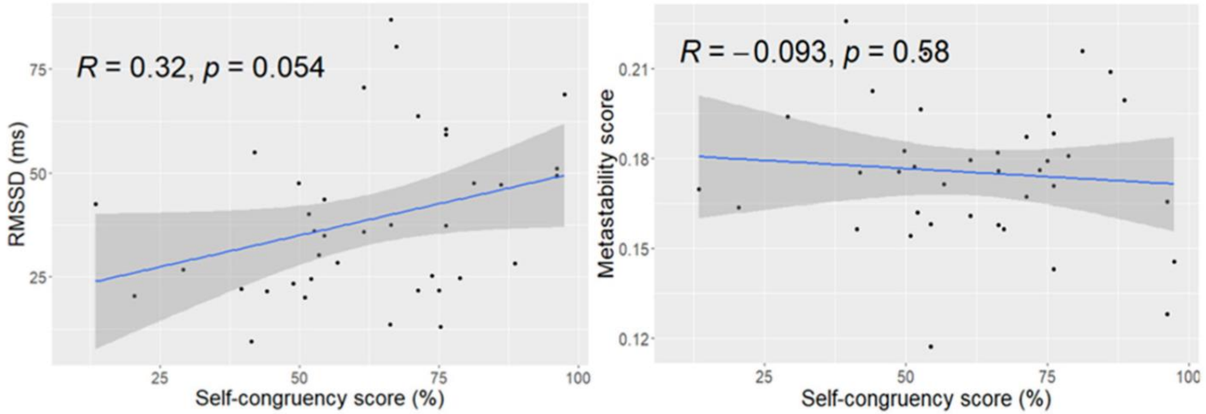
‘Awareness’ beyond ‘brain’ perspective

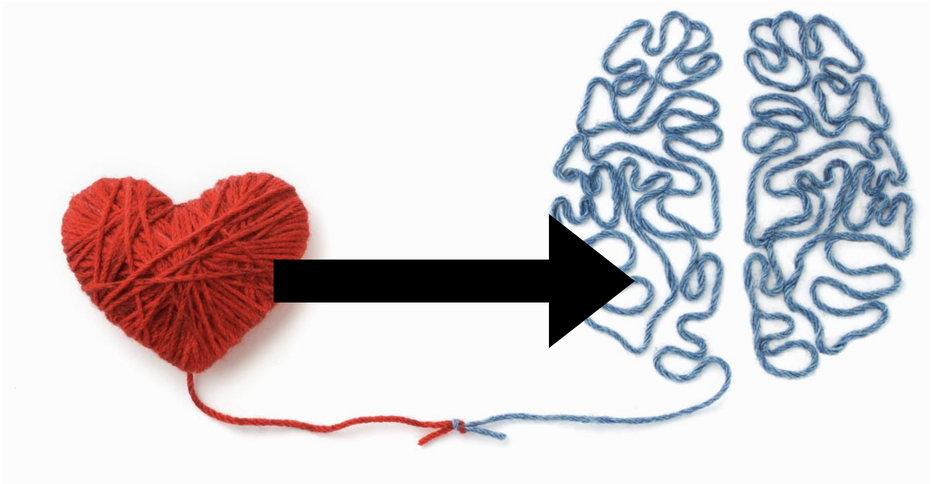


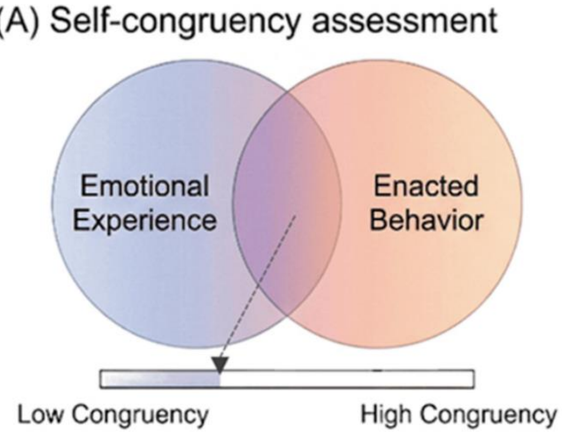


Bourdillon, N.; Urben, S.; Rimorini, N.; Rey, A.; Besson, C.; Ledoux, J.-B.; Alemán-Gómez, Y.; Fornari, E.; Denervaud, S. Heart–Brain Temporal Coupling as a Candidate Biomarker of Self-Congruency. *Biomedicines* **2026**, *14*, 548. https://doi.org/10.3390/biomedicines14030548

‘Awareness’ beyond ‘brain’ perspective







(B) Heart–brain covariance associated with self-congruency.

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Thank you very much