(In)Flexible learning behavior in autism through the lens of reinforcement learning

Lei Zhang

Social, Cognitive and Affective Neuroscience Unit (SCAN-Unit)

Faculty of Psychology, University of Vienna

April 17, 2021

lei.zhang@univie.ac.at

lei-zhang.net

@lei_zhang_lz

SCAN Unit

universität wien

Fakultät für Psychologie

Outline

- The emergence of Computational Psychiatry (CP)
- A case study: flexible choice behavior in Autism
- hBayesDM: a toolbox for estimating hierarchical Bayesian models
- Summary

Outline

- The emergence of Computational Psychiatry (CP)
- A case study: flexible choice behavior in Autism
- hBayesDM: a toolbox for estimating hierarchical Bayesian models
- Summary

Three cultures of CP

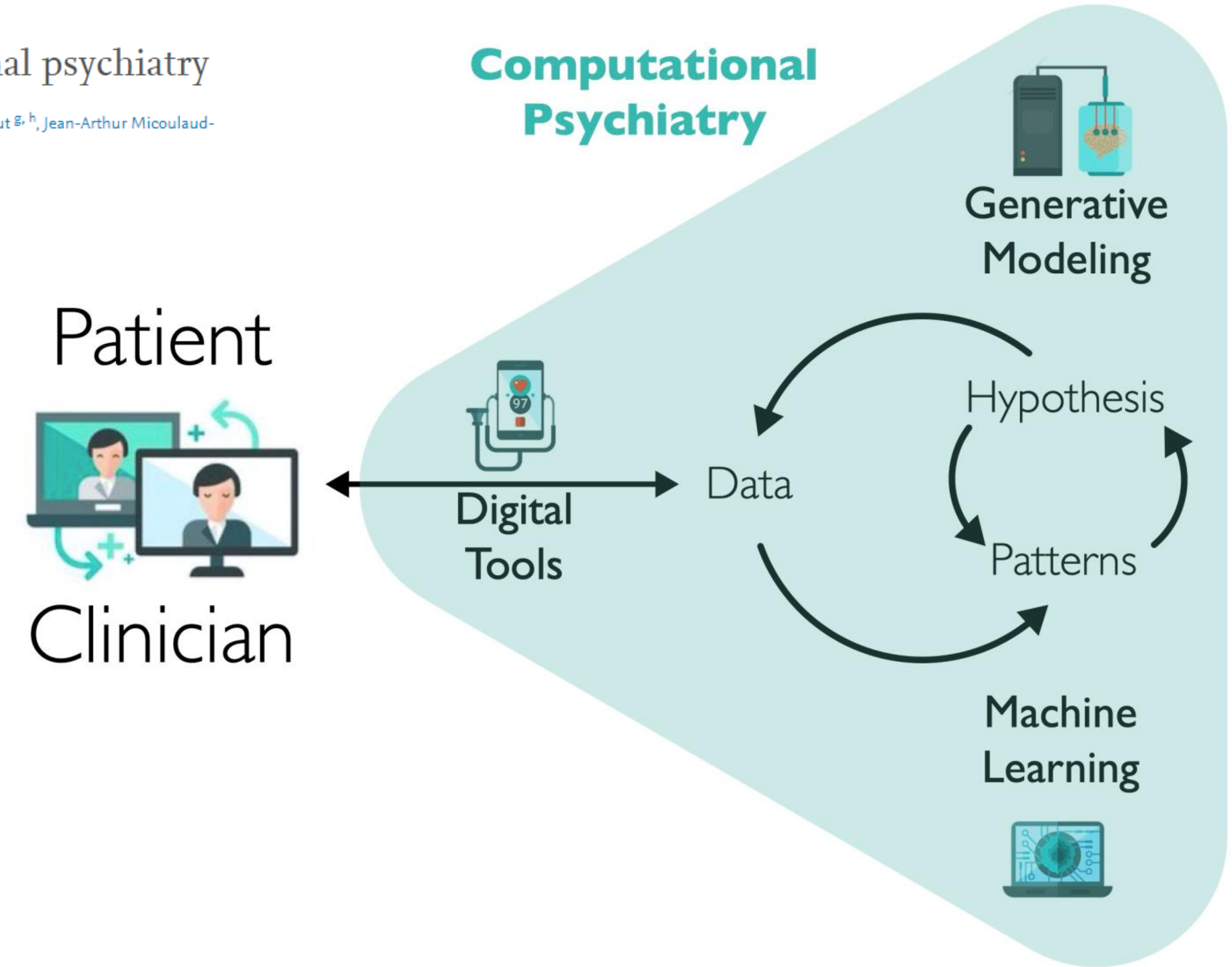
Communication

Les trois cultures de la psychiatrie computationnelle

The three cultures of computational psychiatry

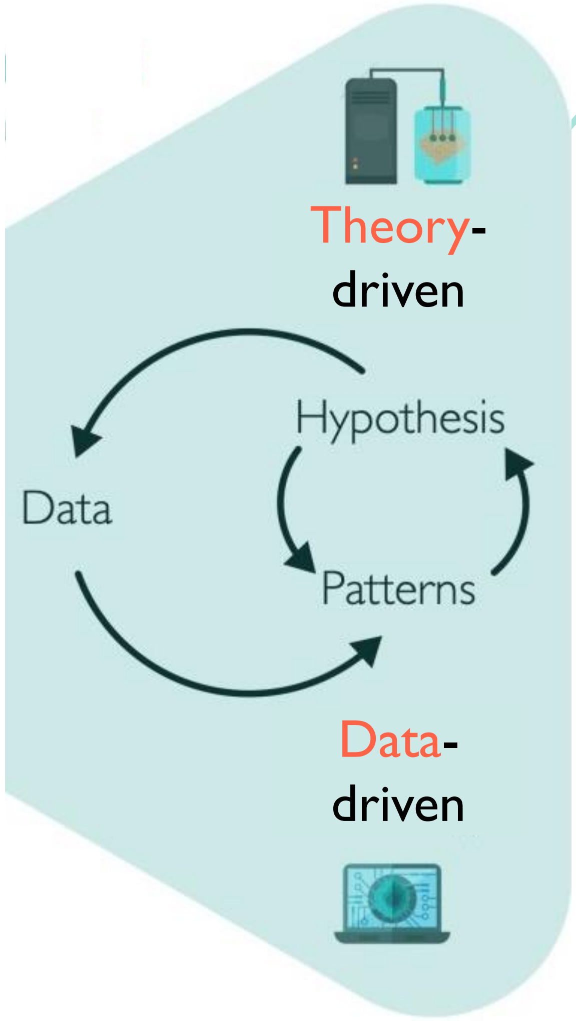
Christophe Gauld [a, b], Guillaume Dumas [c, d], Éric Fakra [e, f], Jérémie Mattout [g, h], Jean-Arthur Micoulaud-Franchi [i, j]

Show more



Gauld et al., (2021)

Theory-driven



Provide mechanistic explanation

Generate prediction/ classification

Construct

RDoC
Research Domain Criteria Initiative

- Reward,
- Learning,
- Self v. Other,
- etc.

Computational modeling

On the role of theory and modeling in neuroscience

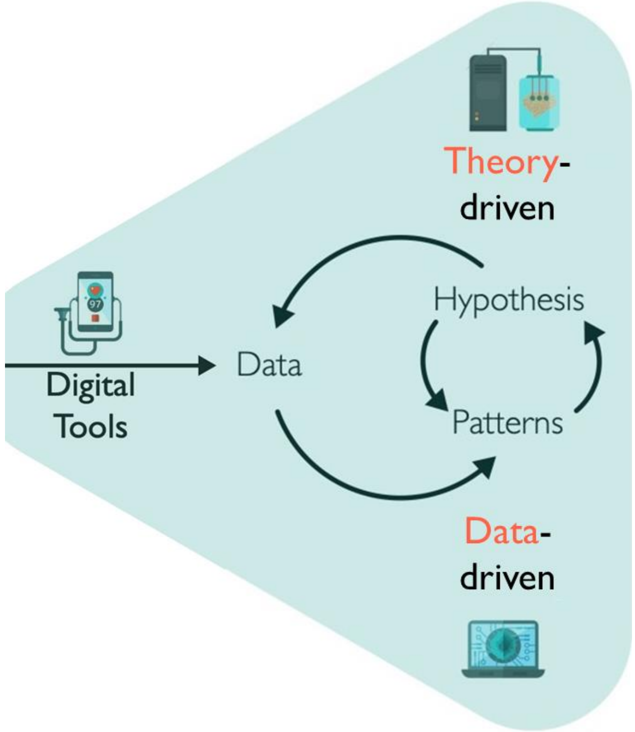
Daniel Levenstein[1], Veronica A. Alvarez[2], Asohan Amarasingham[14], Habiba Azab[3], Richard C. Gerkin[4], Andrea Hasenstaub[5], Ramakrishnan Iyer[6], Renaud B. Jolivet[7], Sarah Marzen[12], Joseph D. Monaco[8], Astrid A. Prinz[13], Salma Quraishi, Fidel Santamaria[9], Sabyasachi Shivkumar[15], Matthew F. Singh[10], David B. Stockton, Roger Traub[11], Horacio G. Rotstein[16,*], Farzan Nadim[16,*], A. David Redish[17,*]

How Computational Modeling Can Force Theory Building in Psychological Science

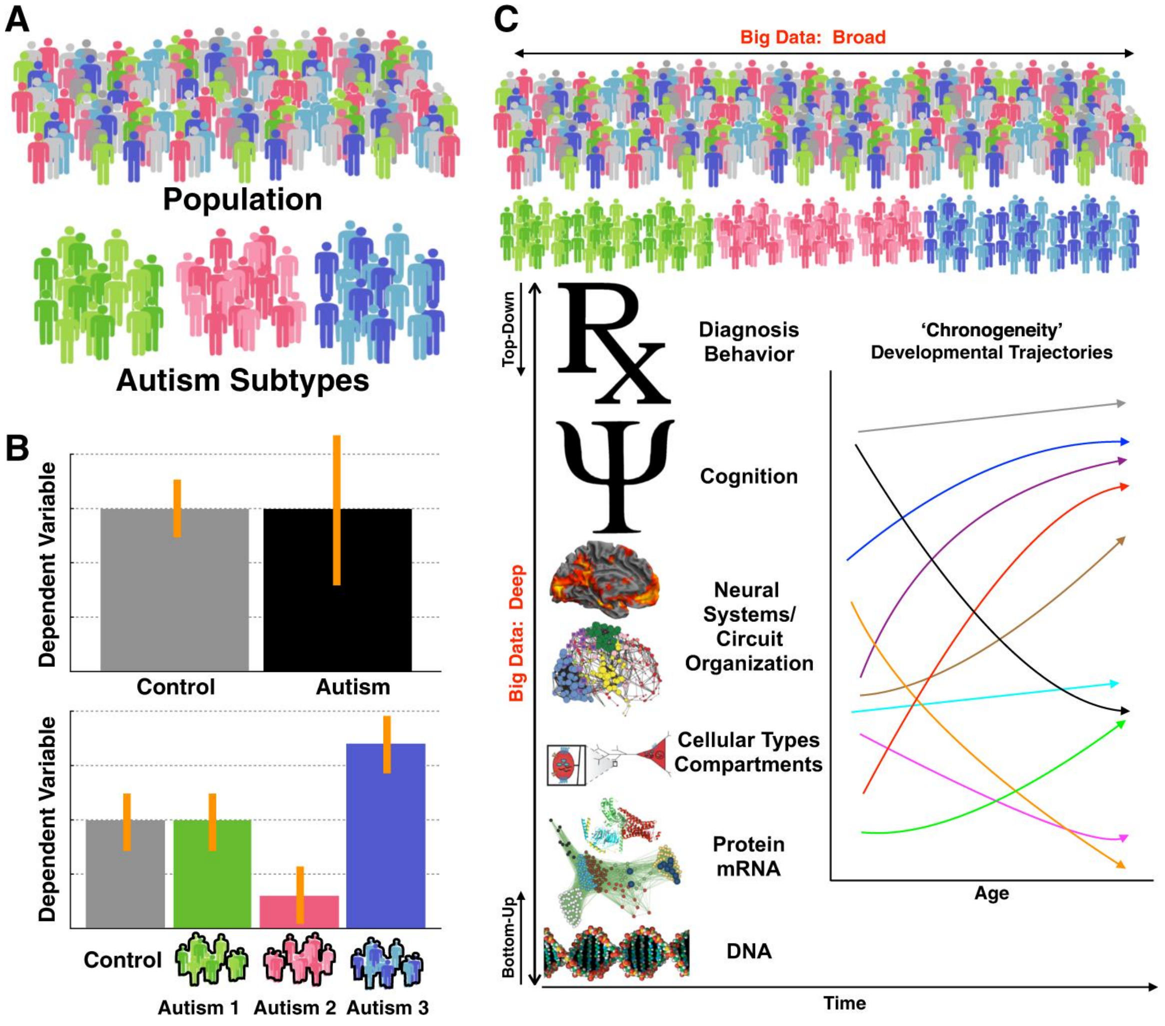
Olivia Guest, Andrea E. Martin

Huys et al., (2016); Paulus, (2017); Bennett et al., (2019); Gauld et al., (2021)

Data-Driven

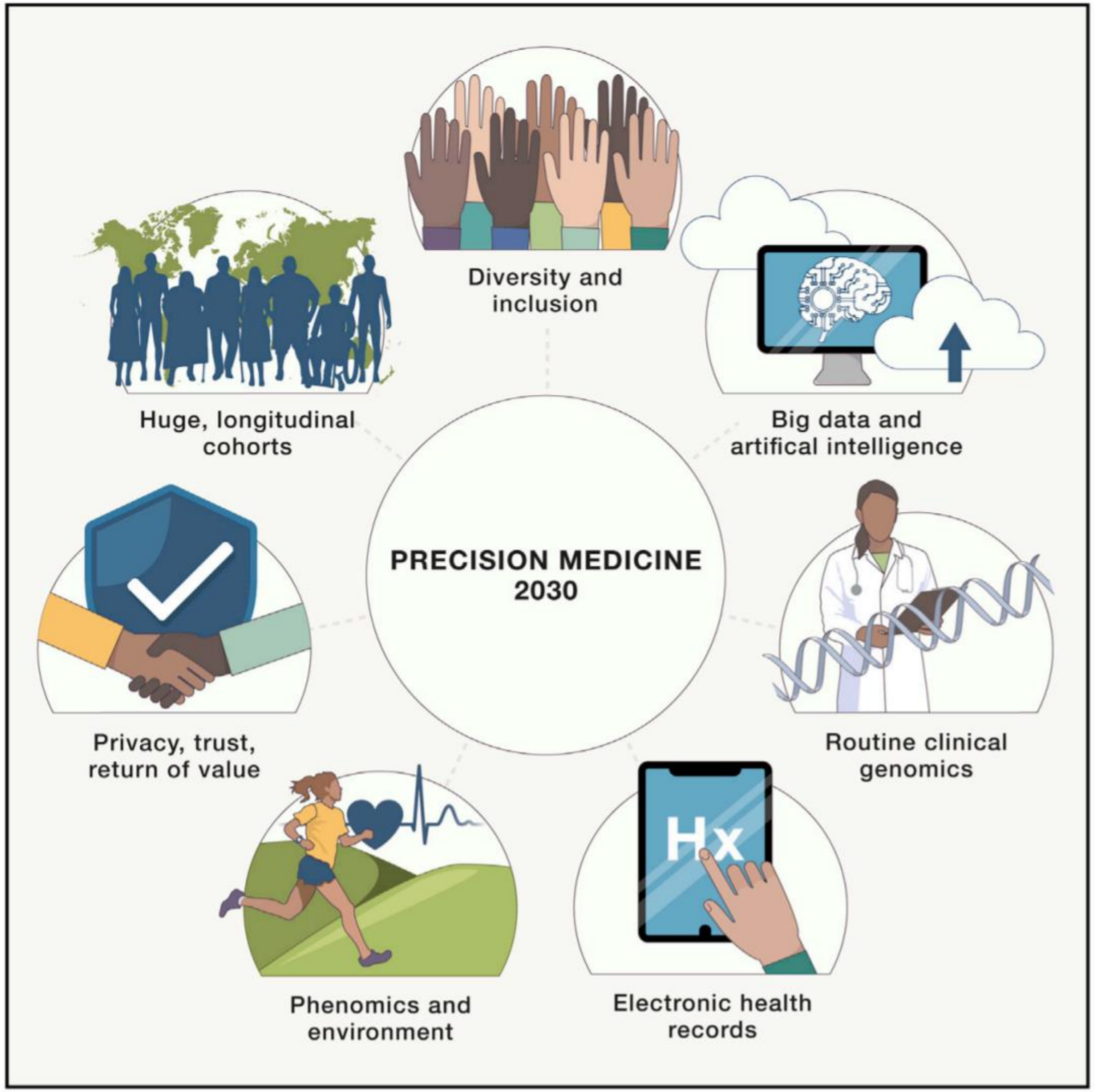


- Diagnostic
- Treatment response
- Identify sub-groups
- Speech analysis



Loth (2016); Lombardo et al. (2019)

Precision medicine in 2030



Denny & Collins (2021)

Figure 1. Seven opportunities for precision medicine by 2030

Computational modeling

Cognition as information processing

Input

Output

$$y = f(x)$$

'Some math happens'

Computational modeling

Cognition as information processing

Behavior

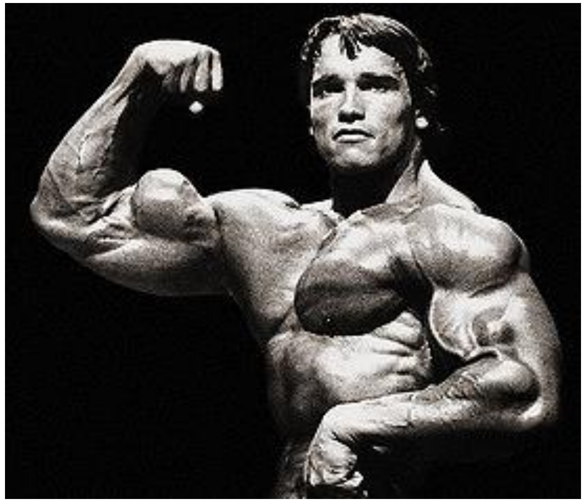
$$B = f(P, E)$$

Person Environment

Kurt Lewin, (1936)

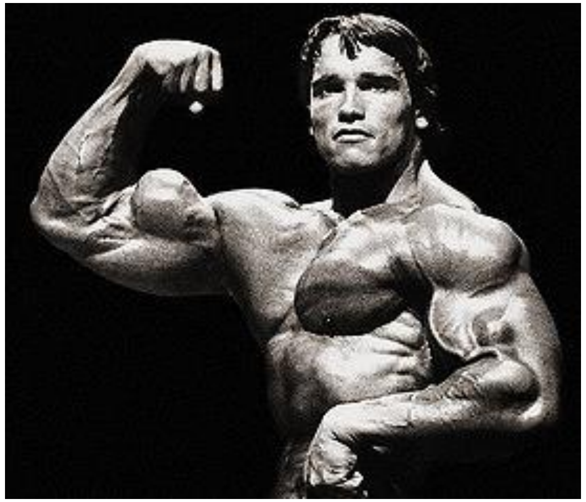
Computational Psychiatry

Wrong problem



Wrong solution

Wrong environment



Adapted from Peter Dayan's Talk

Outline

- The emergence of Computational Psychiatry (CP)
- A case study: flexible choice behavior in Autism
- hBayesDM: a toolbox for estimating hierarchical Bayesian models
- Summary

Case study

Flexible learning behavior in autism

(Crawley* & <u>Zhang*</u> et al., 2020, *Plos Biology*)

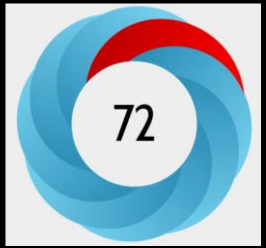
*: joint first author

PLOS BIOLOGY

RESEARCH ARTICLE

Modeling flexible behavior in childhood to adulthood shows age-dependent learning mechanisms and less optimal learning in autism in each age group

Daisy Crawley[1‡*], Lei Zhang[2,3,4‡], Emily J. H. Jones[5], Jumana Ahmad[1,6], Bethany Oakley[1], Antonia San José Cáceres[1,7], Tony Charman[8,9], Jan K. Buitelaar[10,11,12], Declan G. M. Murphy[1,9,13], Christopher Chatham[4], Hanneke den Ouden[10‡], Eva Loth[1,13‡], the EU-AIMS LEAP group[¶]



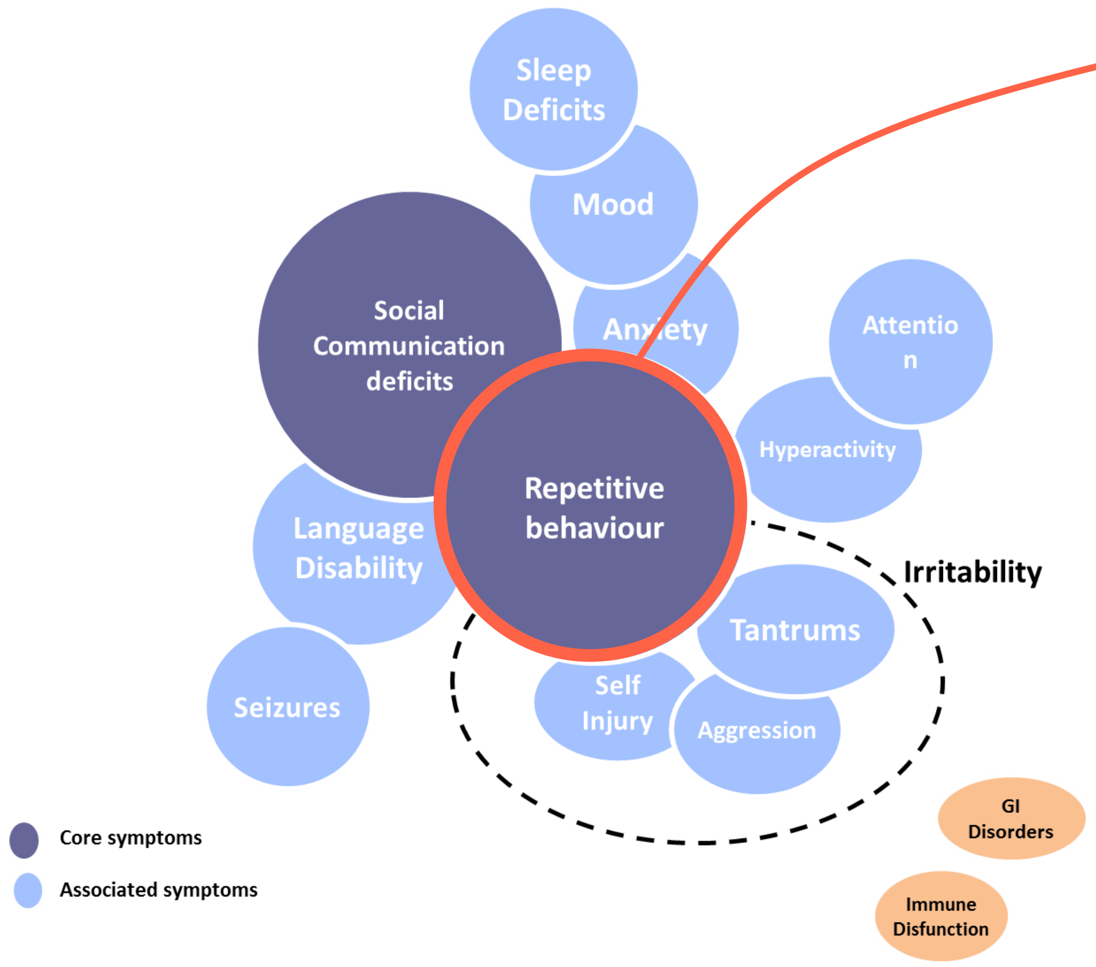
Autism spectrum disorders

Autism is a developmental disorder characterized by difficulties with social interaction and communication, and by restricted and repetitive behavior.[3] Parents often notice signs during the first three years of their child's life.[1][3] These signs often develop gradually, though some autistic children experience regression in their communication and social skills after reaching developmental milestones at a normal pace.[14]

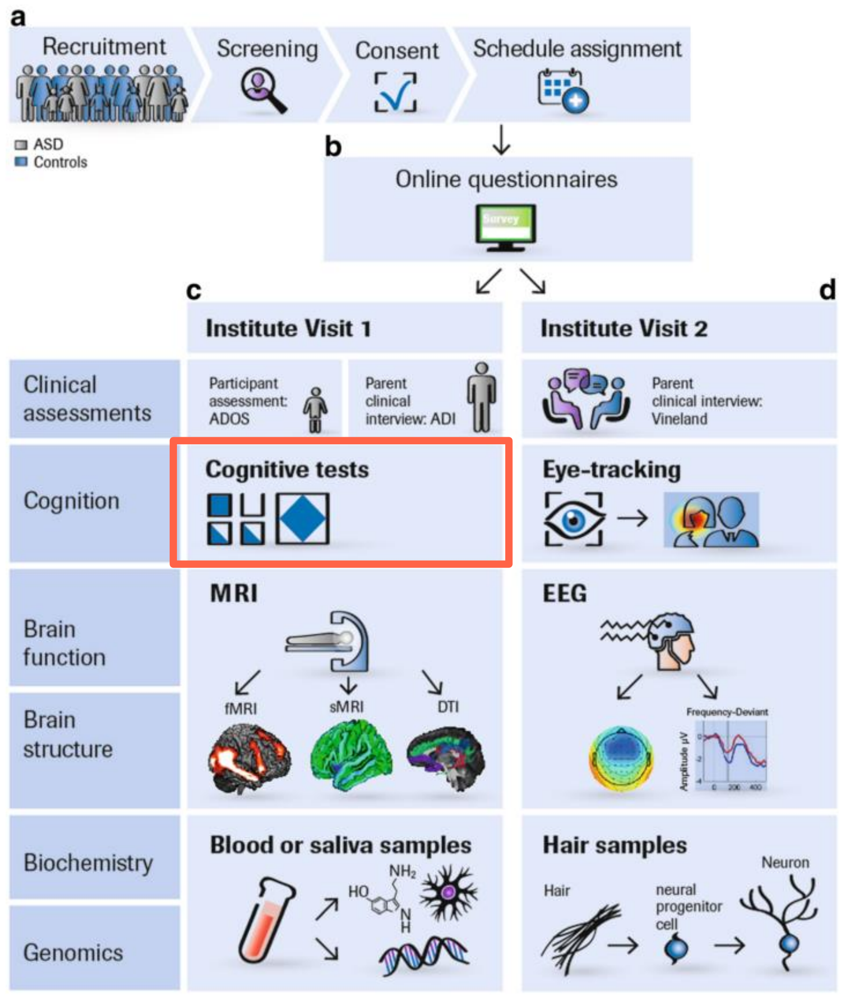
- In 2020, the CDC reported that approximately 1 in 54 children in the U.S. is diagnosed with an autism spectrum disorder (ASD), according to 2016 data.
    - 1 in 34 boys identified with autism
    - 1 in 144 girls identified with autism
- Boys are four times more likely to be diagnosed with autism than girls.
- Most children were still being diagnosed after age 4, though autism can be reliably diagnosed as early as age 2.
- 31% of children with ASD have an intellectual disability (intelligence quotient [IQ] <70), 25% are in the borderline range (IQ 71–85), and 44% have IQ scores in the average to above average range (i.e., IQ >85).

https://www.autismspeaks.org/

Impaired cognitive flexibility in Autism



Behavioral rigidity is underpinned by cognitive (in)flexibility



DSM-V; Loth et al., (2017)

Impaired cognitive flexibility

26 Review TRENDS in Cognitive Sciences Vol.8 No.1 January 2004

ELSEVIER

Executive dysfunction in autism☆

Elisabeth L. Hill

Department of Psychology, Goldsmiths College, University of London, Whitehead Building, New Cross, London, SE14 6NW, UK

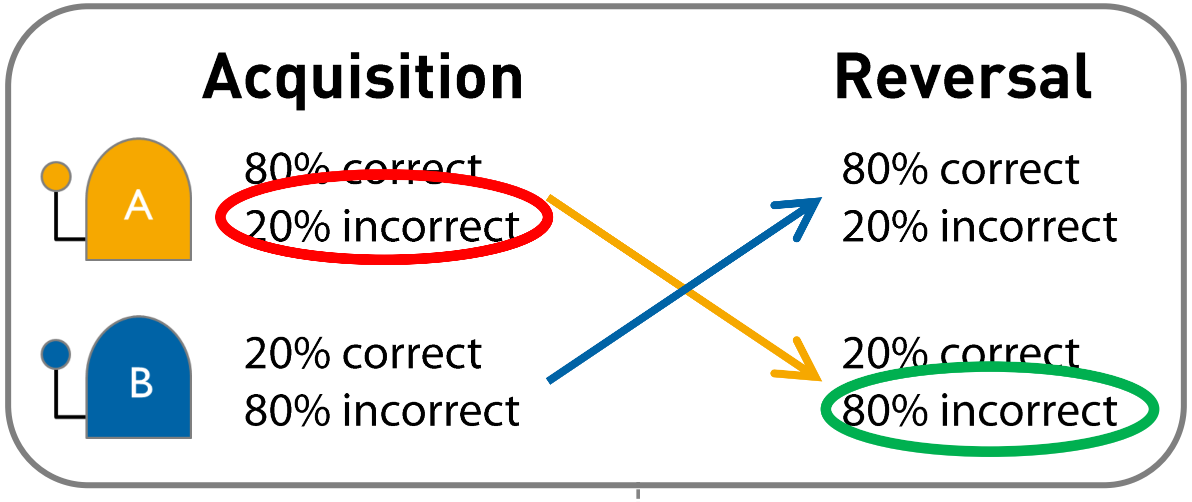
- Behavioural rigidity may be underpinned by cognitive (in)flexibility

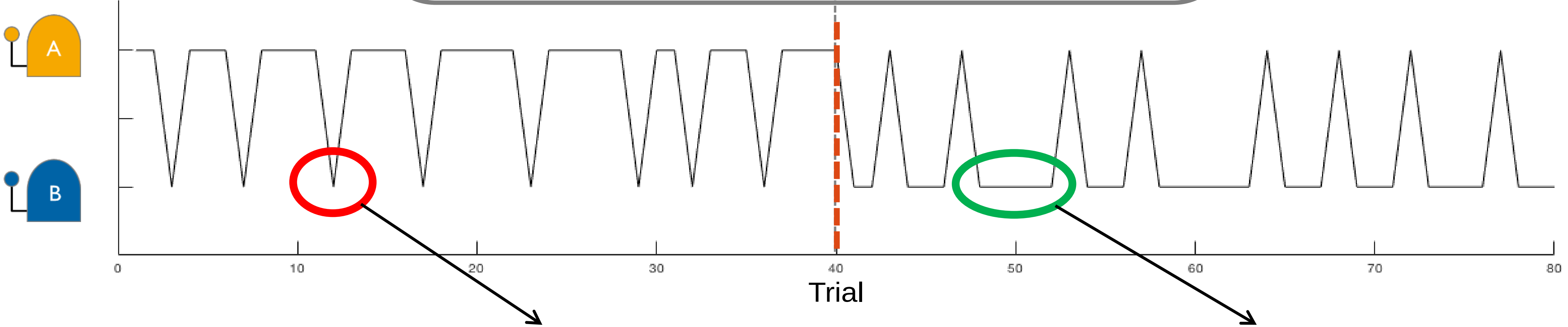
- Repetitive motor movements
- Insistence on **sameness**
- **Inflexible** adherence to routines
- Ritualised patterns of behaviour
- **Difficulties** with **transitions**
- **Rigid thinking patterns**
- Restricted play
- Circumscribed interests

- 'The ability to **shift between** different tasks or goals
- 'The ability to **shift** to different thoughts or actions **depending on situational demands**'
- 'Capacity to **adjust** one's thoughts or actions **in response to** situational **changes**'

Miyake et al., (2000); Monsell, (2003); Geurts et al., (2009); Costescu et al., (2015)

Cognitive flexibility in reversal learning



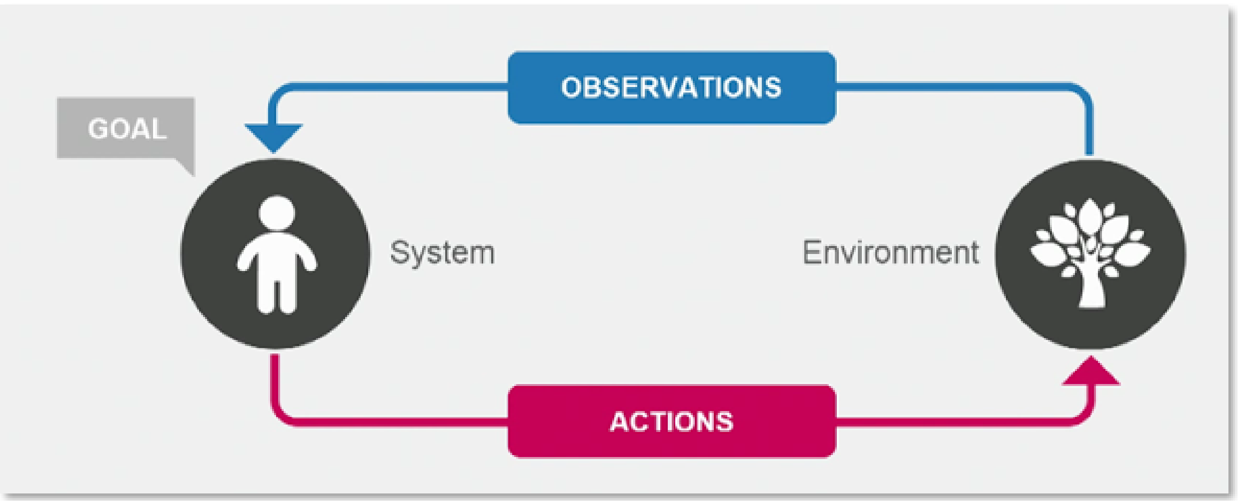


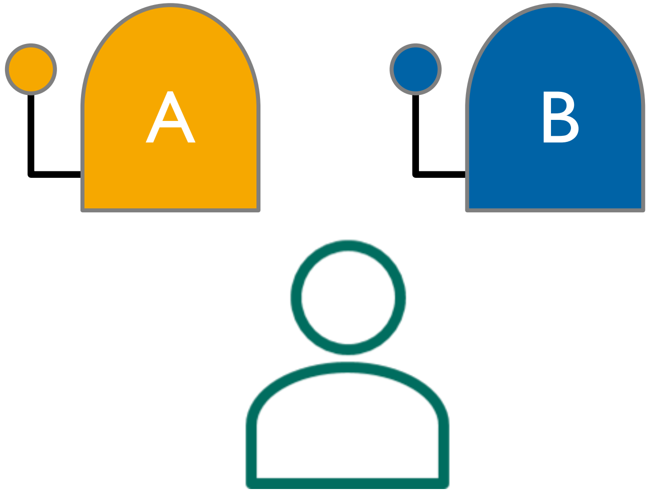
Rare outcome
needs to be ignored

Common outcome
needs to be learned

Cools et al., (2002); den Ouden et al., (2013); Izquierdo et al., (2017)

Computational focus





Reinforcement learning

- gain reward/avoid punishment
- feedback-driven, trial-and-error

Rescorla-Wagner Model

Value update: $V_t = V_{t-1} + \alpha * \mathrm{PE}_{t-1}$

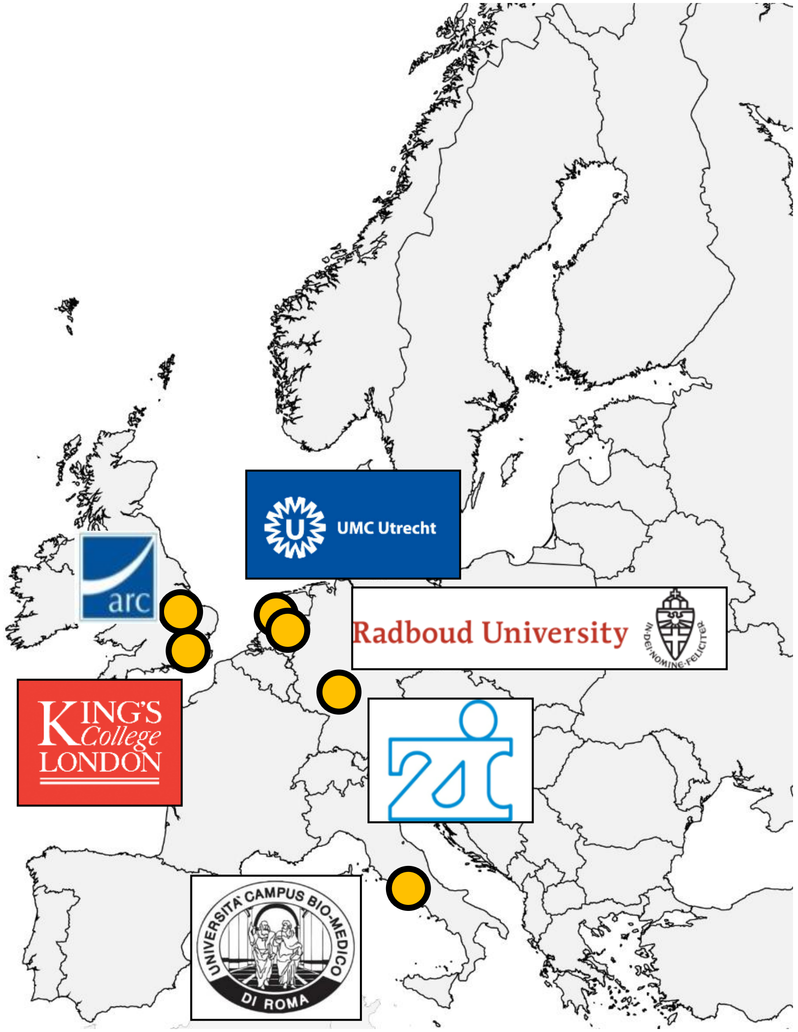
Prediction error: $\mathrm{PE}_{t-1} = R_{t-1} - V_{t-1}$

*Expectations on the next trial = the expectation on the current trial + learning rate * prediction error (reward – current expectation)*

Sutton & Barto, (2018); Rescorla & Wagner, (1972)

EU-AIMS LEAP

Longitudinal European Autism Project

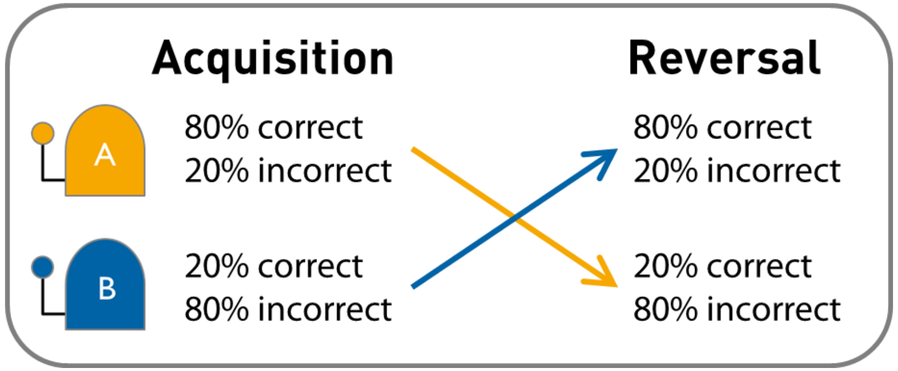


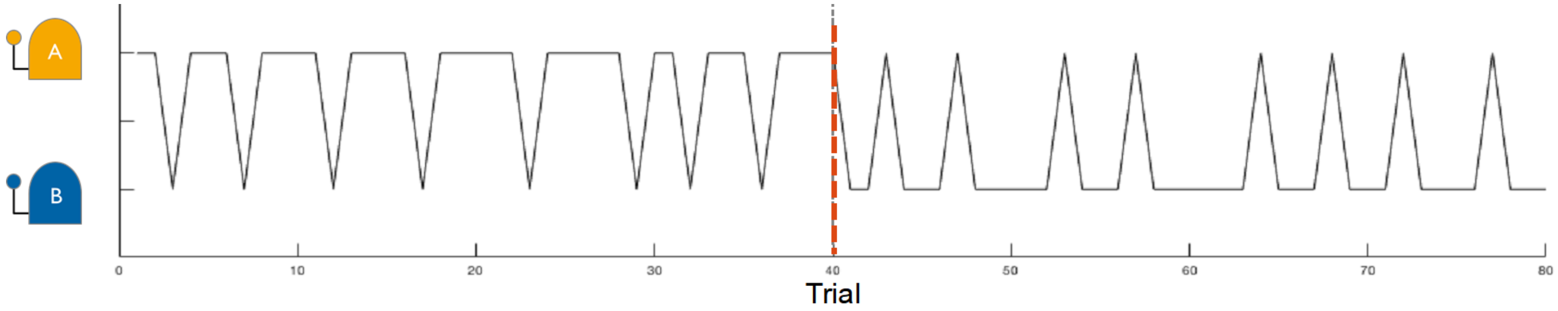
		Diagnosis		
		ASD	TD	Total
Age group	Children (6-11 years)	81	64	145
	Adolescents (12-17 years)	114	90	204
	Adults (18-30 years)	126	97	223
	Total	321	251	572

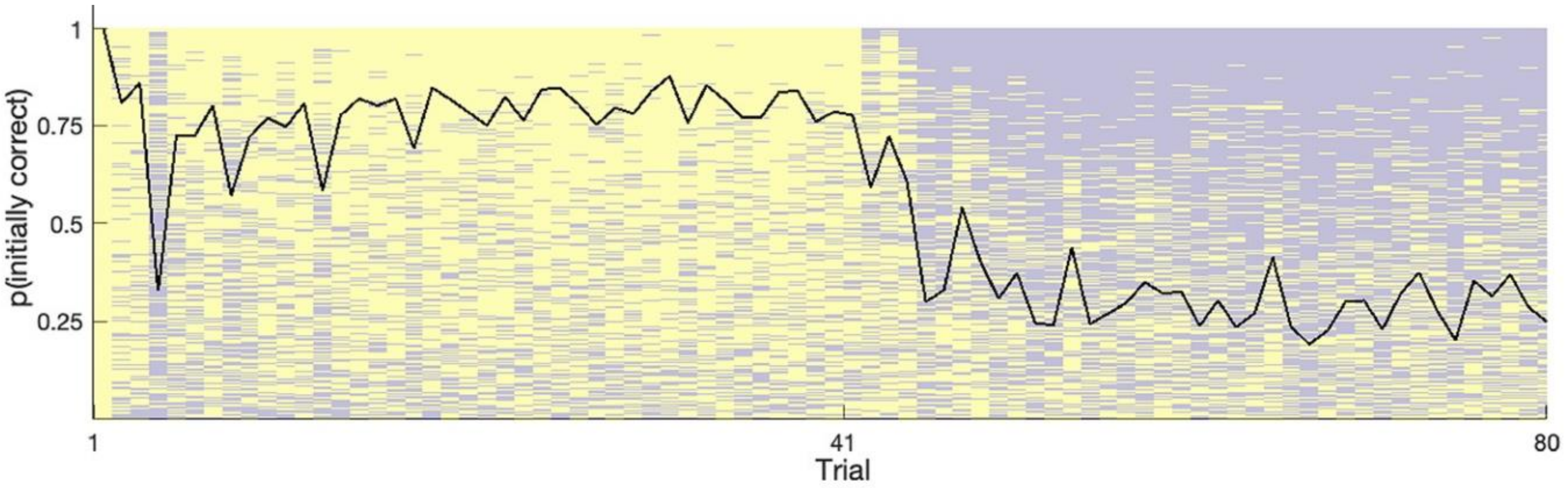
- ASD = Autism spectrum disorder
- TD = Typical development

Loth et al., (2017); Crawley* & Zhang* et al., *PLoS Biology*, (2020)

Paradigm

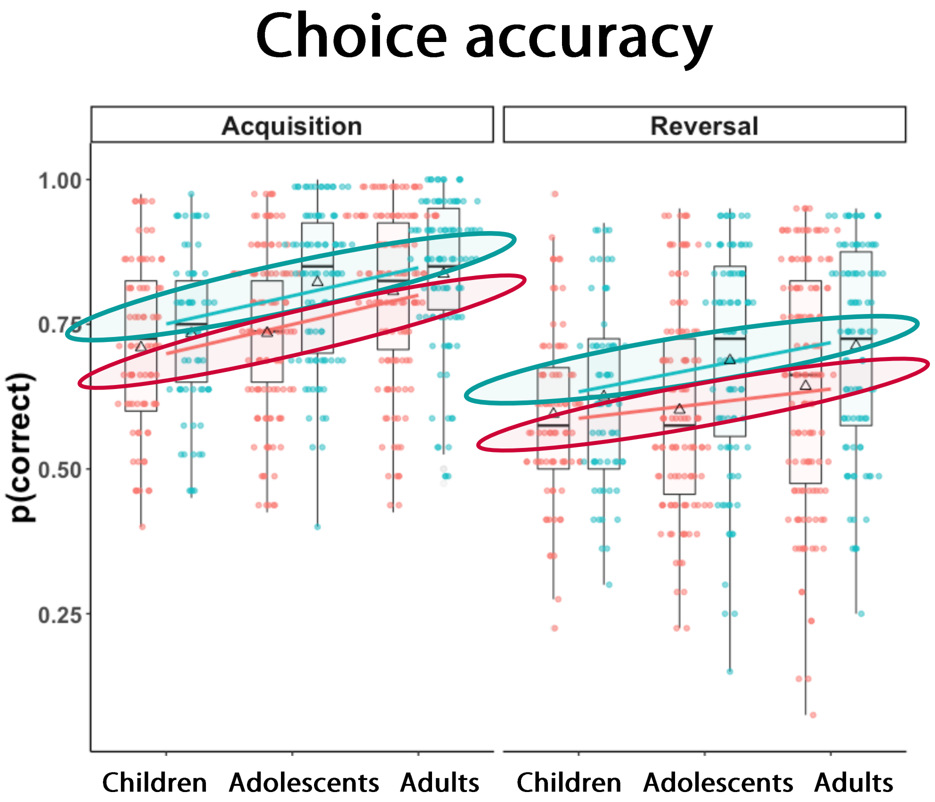


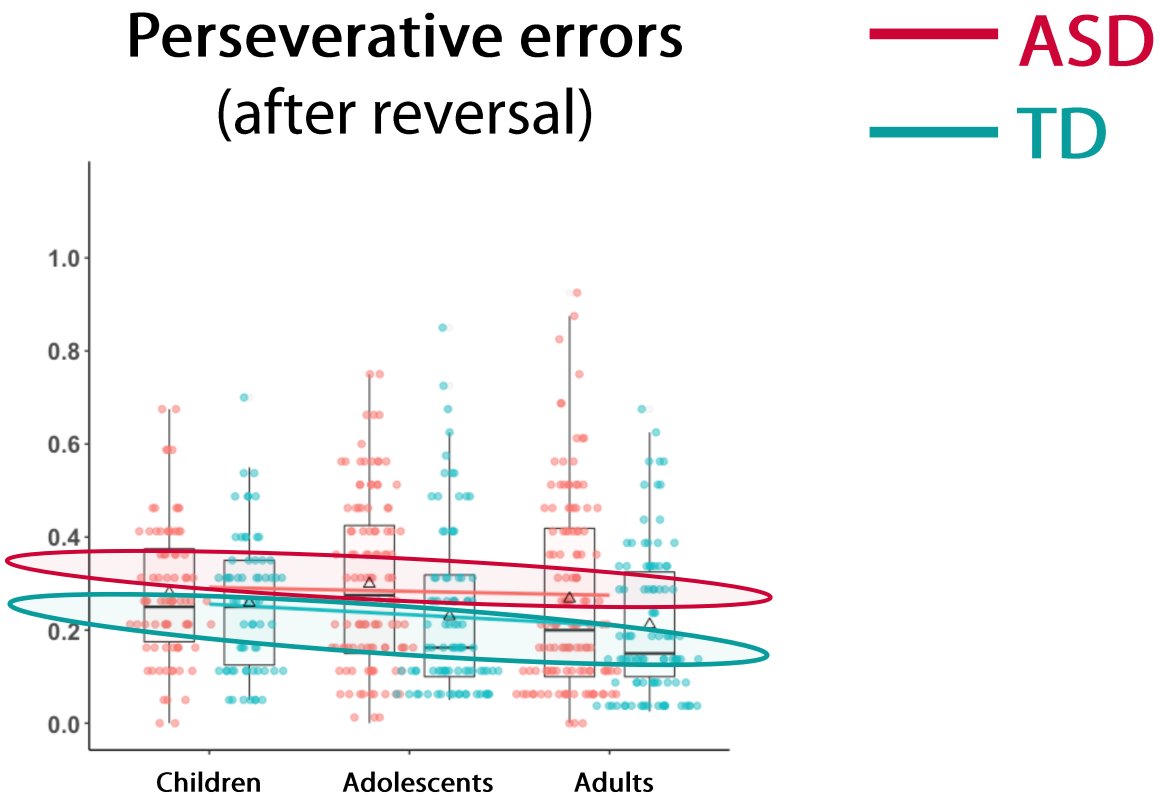




Crawley* & Zhang* et al., *PLoS Biology*, (2020)

Less optimal learning performance in ASD

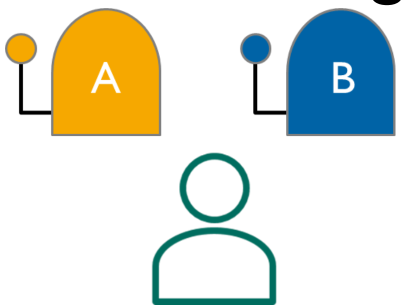




Crawley* & Zhang* et al., *PLoS Biology*, (2020)

What to model?

Decision-making tasks



what do we know? — choice & outcome

what can we measure? — choice accuracy

what do we not know? — computational processed

	subjID	trialID	choice	outcome
1	1	1	1	1
2	1	2	1	1
3	1	3	1	1

Rangel et al (2008)

Model space

Counterfactual update RL

$$V_{c,t} = V_{c,t-1} + \eta\left(O_{t-1} - V_{c,t-1}\right)$$
$$V_{nc,t} = V_{nc,t-1} + \eta\left(-O_{t-1} - V_{nc,t-1}\right)$$

Reward-punishment RL

$$V_{c,t} = \begin{cases} V_{c,t-1} + \eta^{\text{rew}}\left(O_{t-1} - V_{c,t-1}\right), \text{ if } O_{t-1} > 0 \\ V_{c,t-1} + \eta^{\text{pun}}\left(O_{t-1} - V_{c,t-1}\right), \text{ if } O_{t-1} < 0 \end{cases}$$

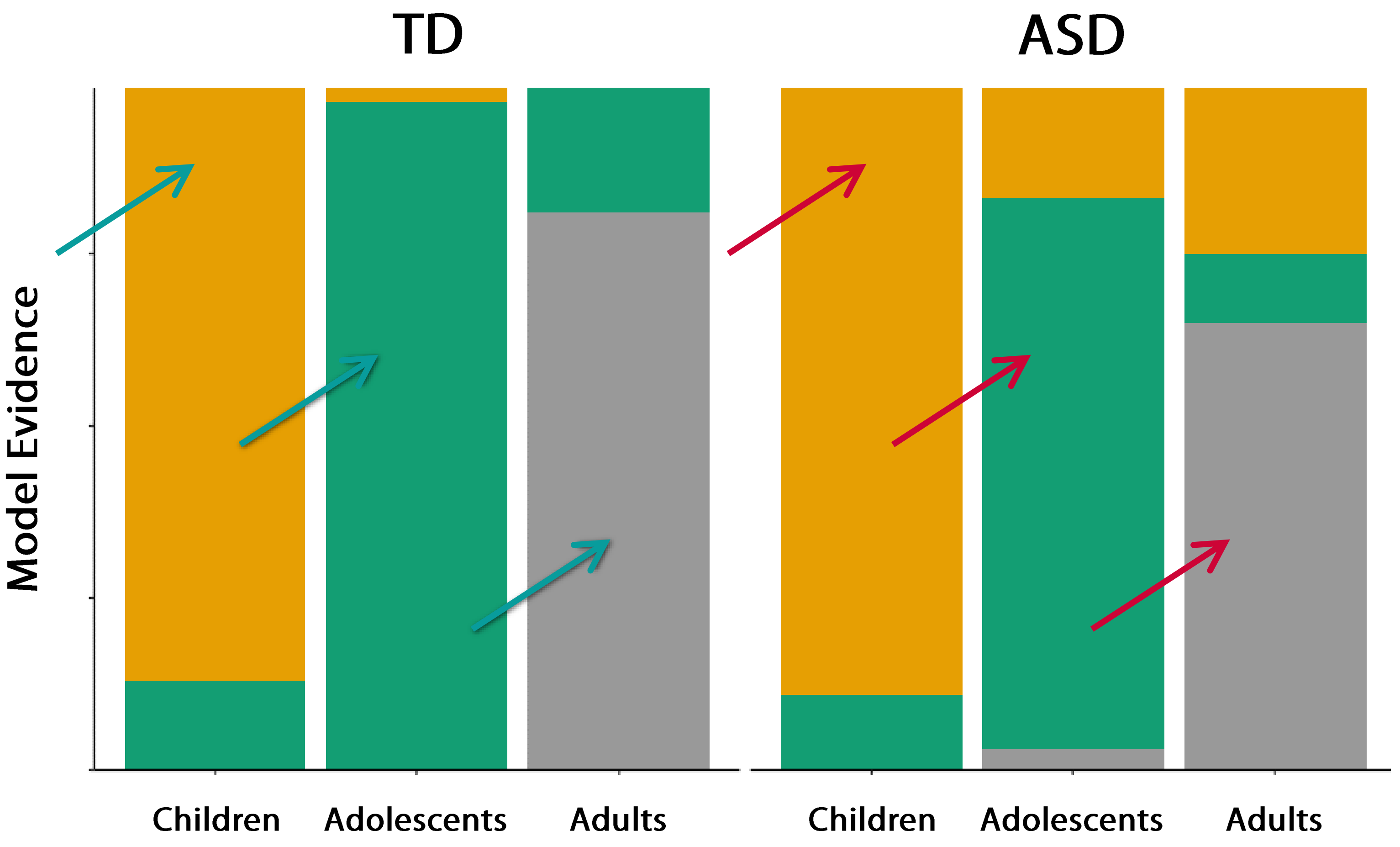
Experience-weighted attraction

$$n_{c,t} = n_{c,t-1} \times \rho + 1$$
$$V_{c,t} = \left(V_{c,t-1} \times \varphi \times n_{c,t-1} + O_{t-1}\right) / n_{c,t}$$

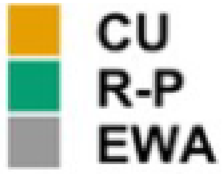
Hampton et al. (2007); den Ouden et al. (2013)

Same computational model within age group

ASD
TD



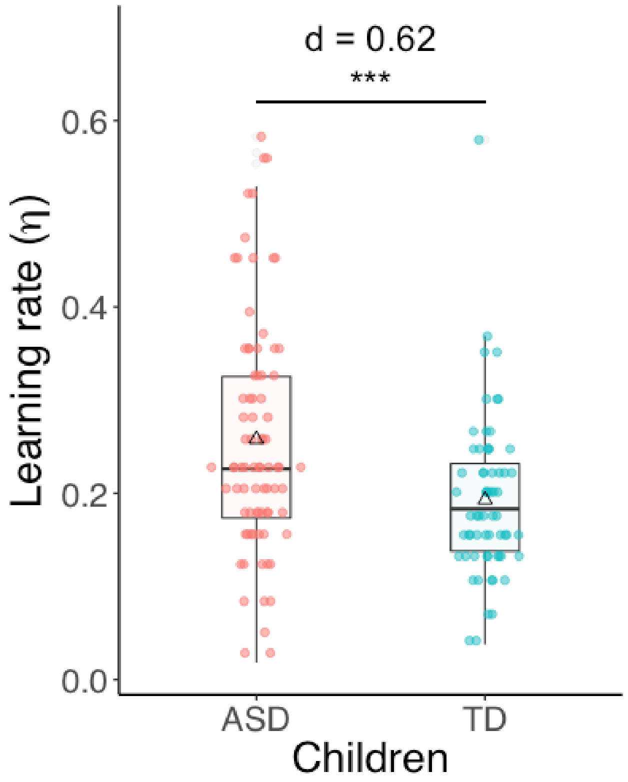
Candidate models originated from Rescorla-Wagner

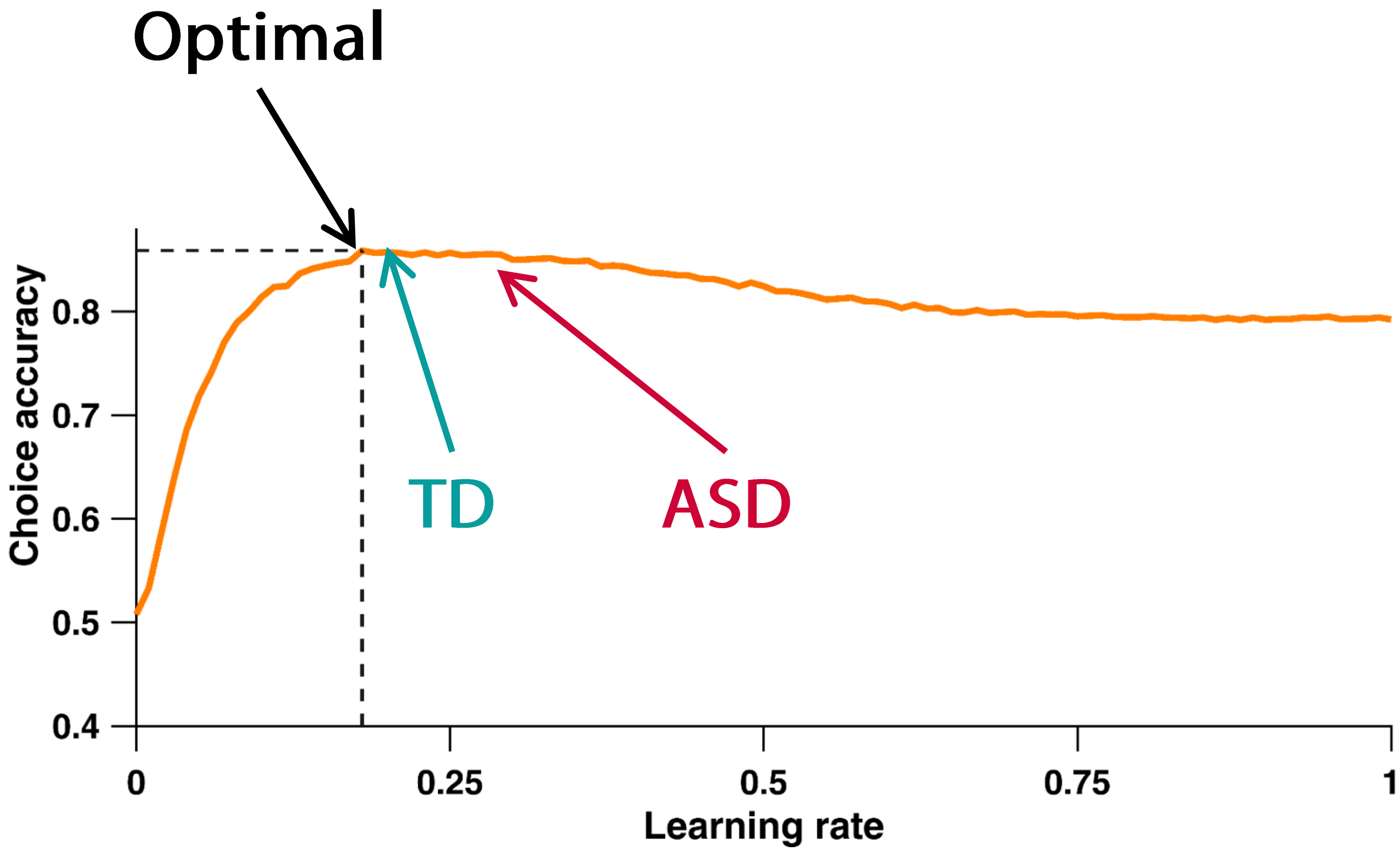


- CU: counterfactual update
- R-P: Reward-punishment
- EWA: Experience-weighted attraction

Crawley* & Zhang* et al., *PLoS Biology*, (2020)

Suboptimal learning parameters in ASD



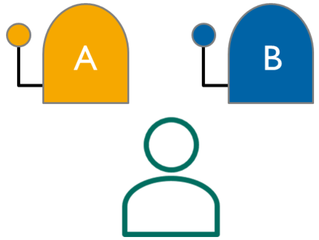


Crawley* & Zhang* et al., *PLoS Biology*, (2020)

Understand the learning rate

Value update: $V_t = V_{t-1} + \alpha * \mathrm{PE}_{t-1}$

Prediction error: $\mathrm{PE}_{t-1} = R_{t-1} - V_{t-1}$



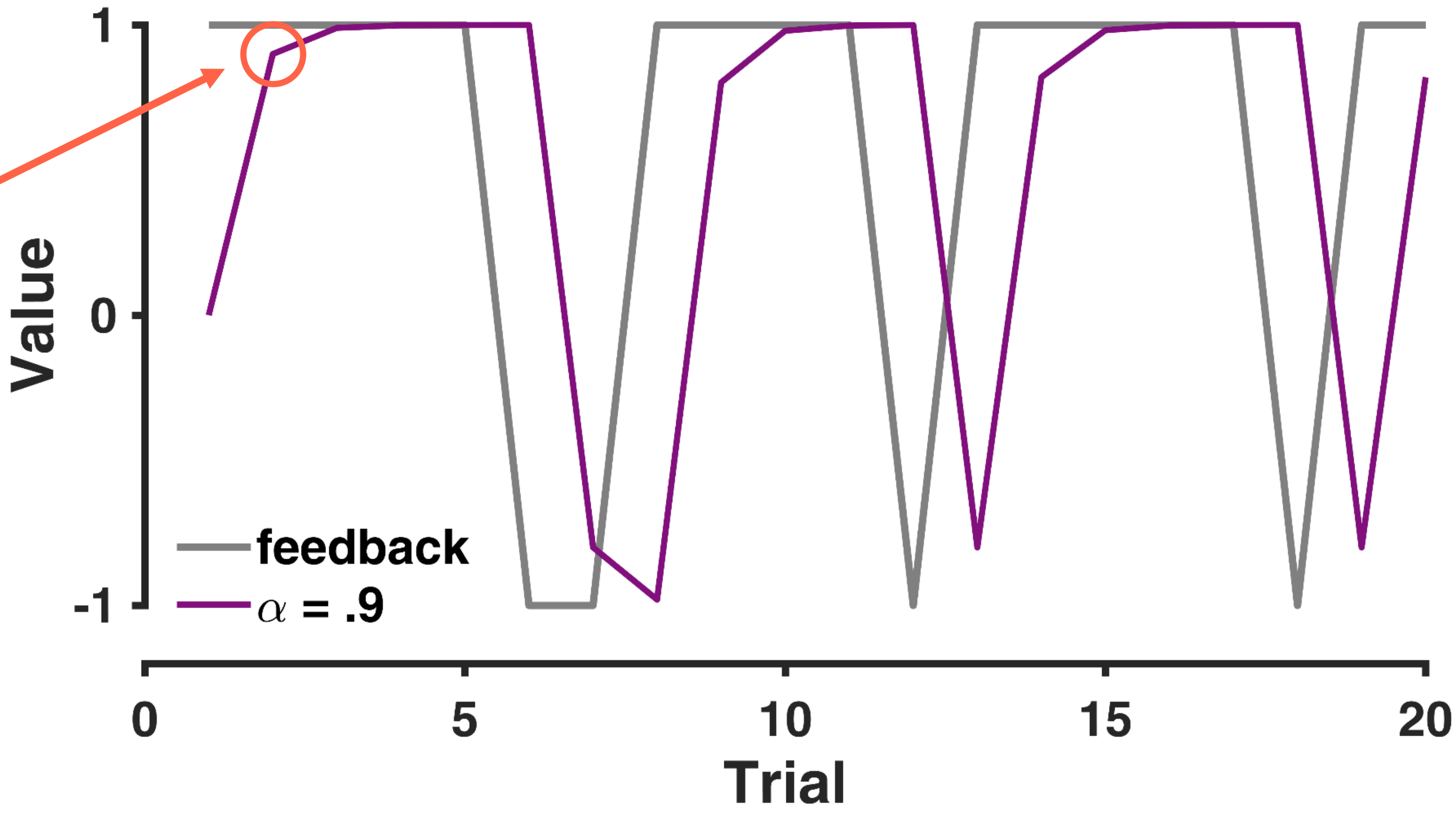
if $\alpha = 0.9$

$V_1 = 0$

$V_2 = V_1 + 0.9 * (1 - V_1)$

$= 0 + 0.9 * (1 - 0)$

$= 0.9$



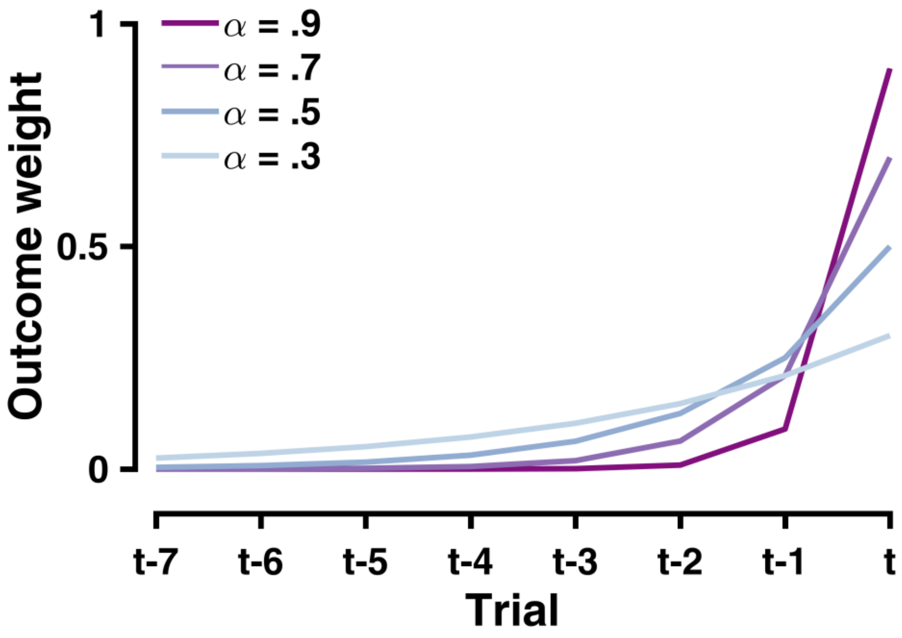
reward contingency – 80:20

Understand the learning rate

Value update: $V_t = V_{t-1} + \alpha * \mathrm{PE}_{t-1}$

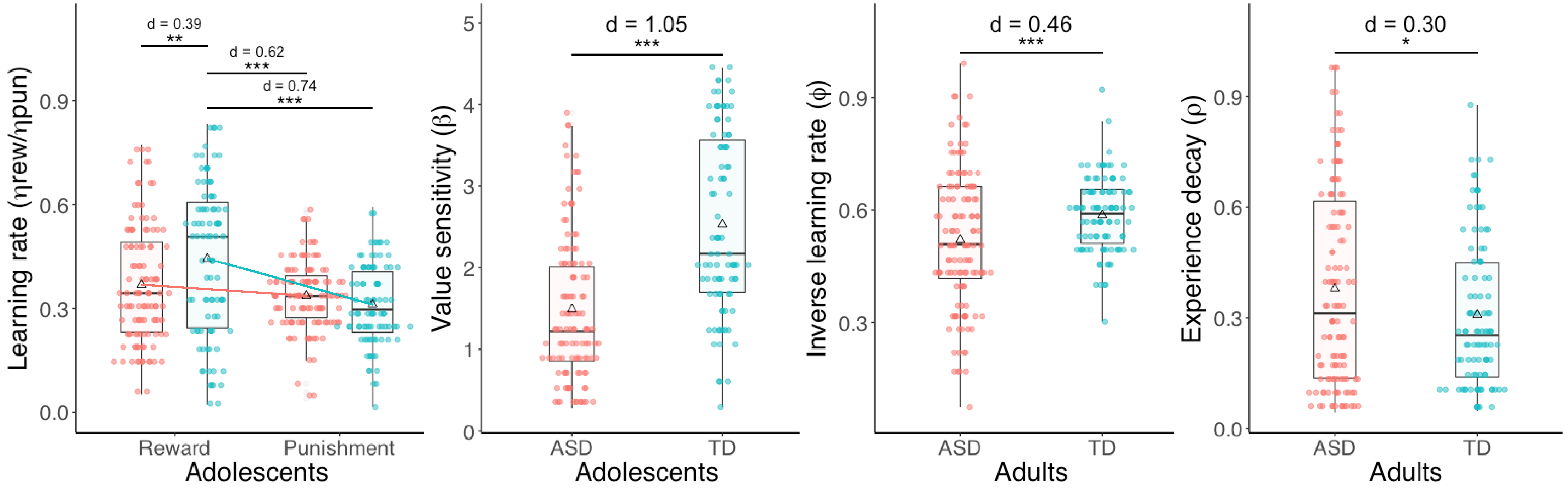
Prediction error: $\mathrm{PE}_{t-1} = R_{t-1} - V_{t-1}$

$$\begin{aligned} V_t &= (1-\alpha)\,V_{t-1} + \alpha R_{t-1} \\ &= (1-\alpha)\,(V_{t-2} + \alpha\,(R_{t-2} - V_{t-2})) + \alpha R_{t-1} \\ &= (1-\alpha)^t V_0 + \boxed{\sum_{i=1}^{t} (1-\alpha)^{t-i} \alpha} R_i \end{aligned}$$



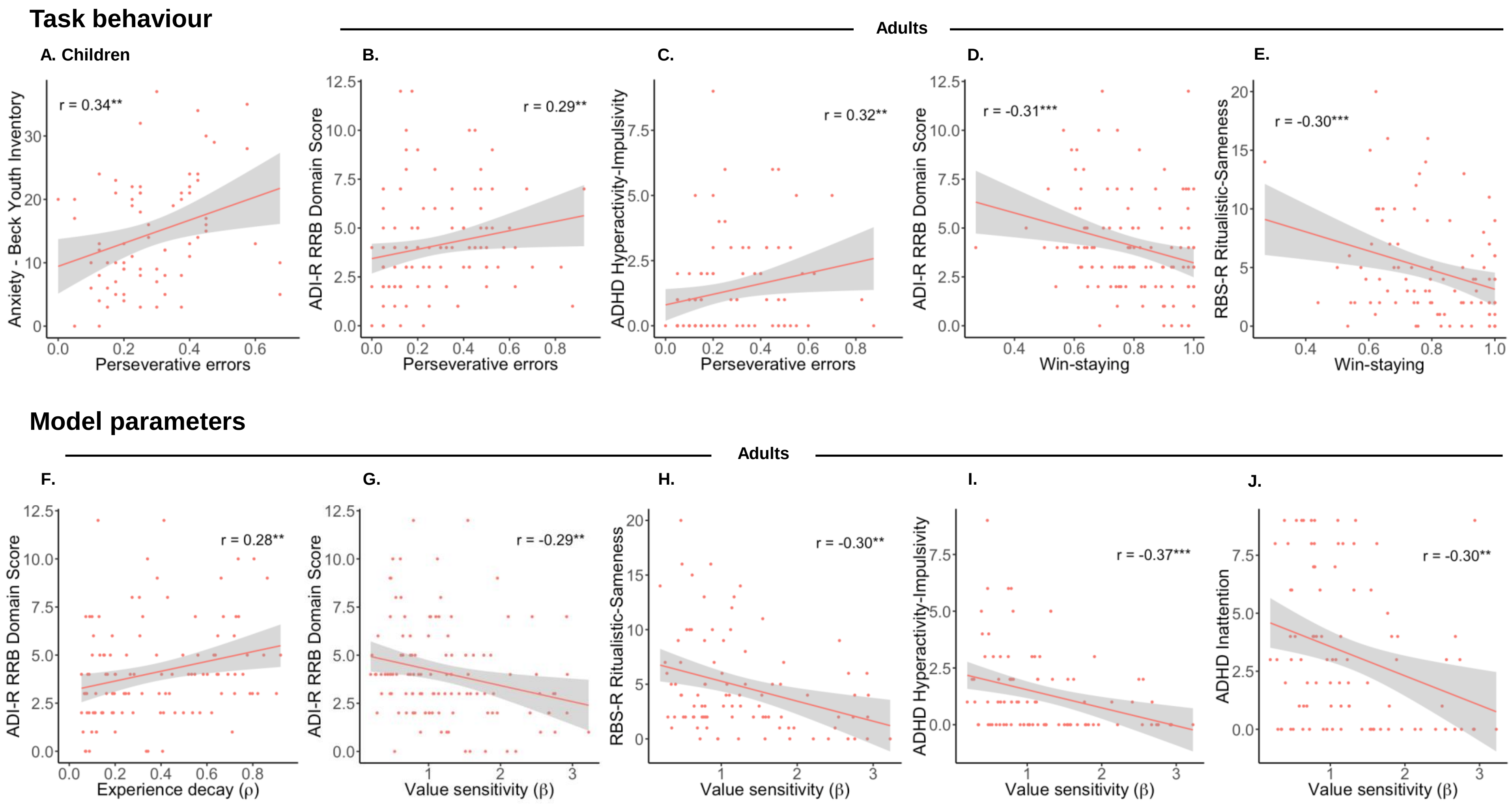
Crawley* & Zhang* et al., *PLoS Biology*, (2020); Zhang et al., *SCAN*, (2020)

Parameter results: less optimal learning



Crawley* & Zhang* et al., *PLoS Biology*, (2020)

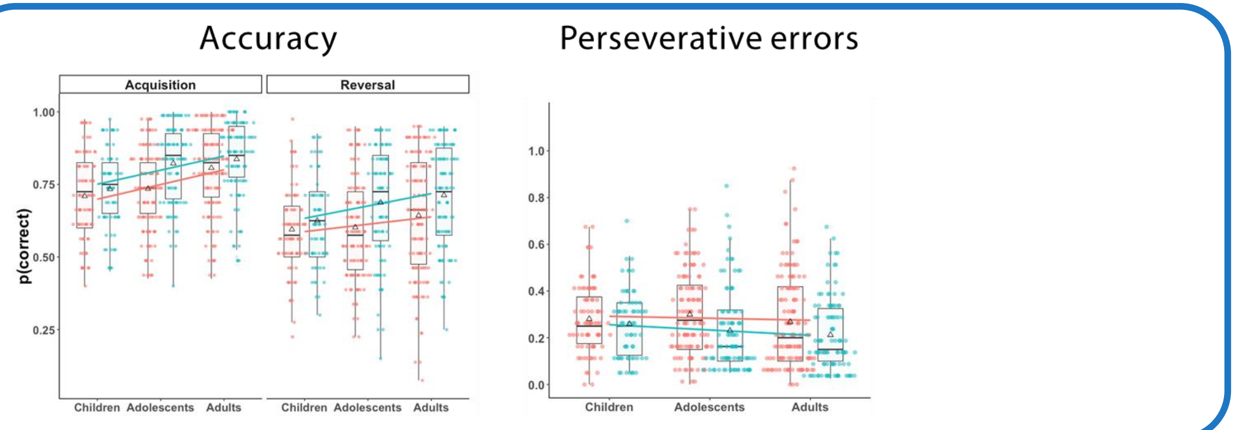
Parameter ~ clinical scales



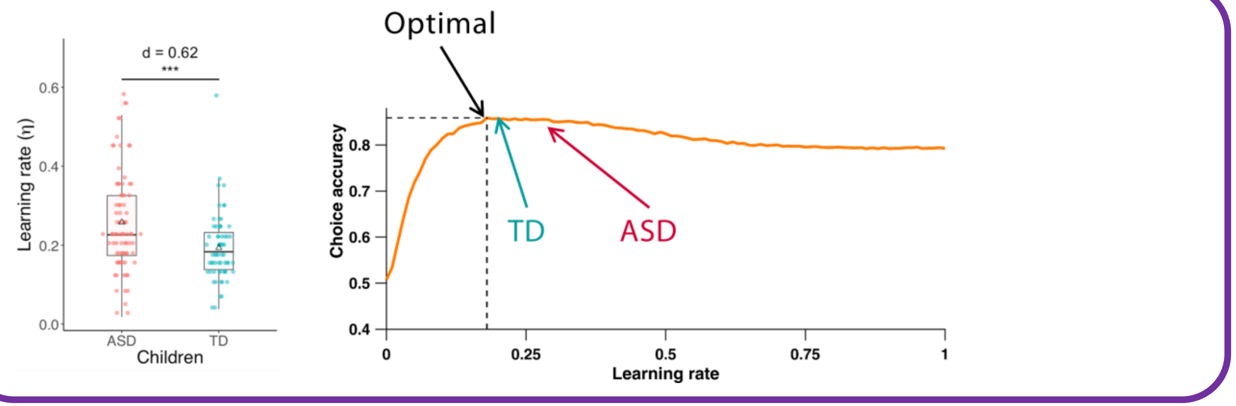
Crawley* & Zhang* et al., *PLoS Biology*, (2020)

Summary

Computation
(why/goal)



Algorithm
(what/rules)



Outline

- The emergence of Computational Psychiatry (CP)
- A case study: flexible choice behavior in Autism
- hBayesDM: a toolbox for estimating hierarchical Bayesian models
- Summary

hBayesDM package

$$V_{c,t} = V_{c,t-1} + \eta\left(O_{t-1} - V_{c,t-1}\right)$$

$$V_{nc,t} = V_{nc,t-1} + \eta\left(-O_{t-1} - V_{nc,t-1}\right)$$

$$V_{c,t} = \begin{cases} V_{c,t-1} + \eta^{\text{rew}}\left(O_{t-1} - V_{c,t-1}\right), \text{ if } O_{t-1} > 0 \\ V_{c,t-1} + \eta^{\text{pun}}\left(O_{t-1} - V_{c,t-1}\right), \text{ if } O_{t-1} < 0 \end{cases}$$

$$n_{c,t} = n_{c,t-1} \times \rho + 1$$

$$V_{c,t} = \left(V_{c,t-1} \times \varphi \times n_{c,t-1} + O_{t-1}\right) / n_{c,t}$$

Stan

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

Ahn, Haines, Zhang, *Computational Psychiatry*, (2017); Zhang & Gläscher, *Science Advances*, (2020)

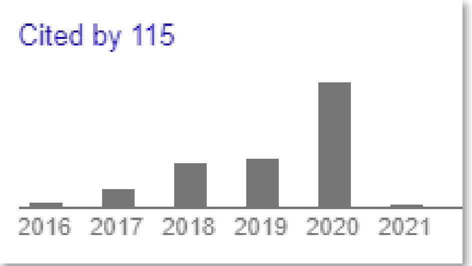
hBayesDM package

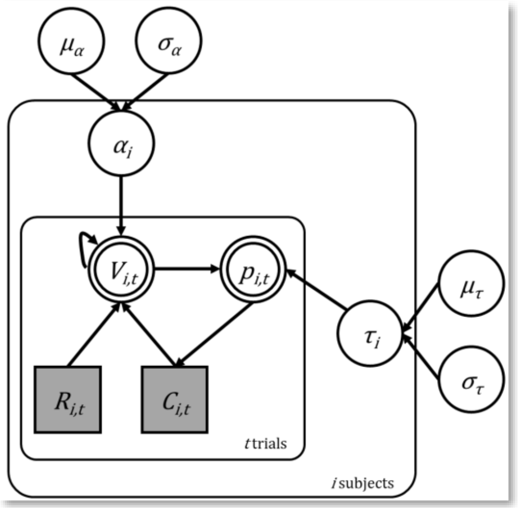
hBayesDM

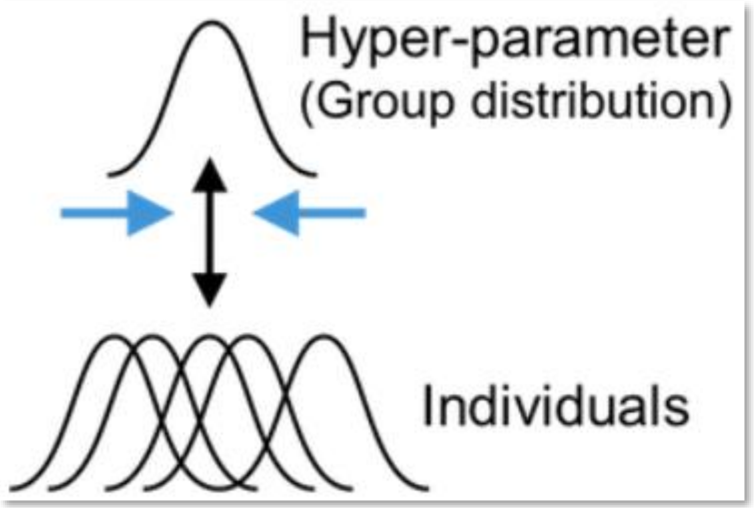
repo status Active | build passing | CRAN 1.0.2 – 2019-11-13 | downloads 33K

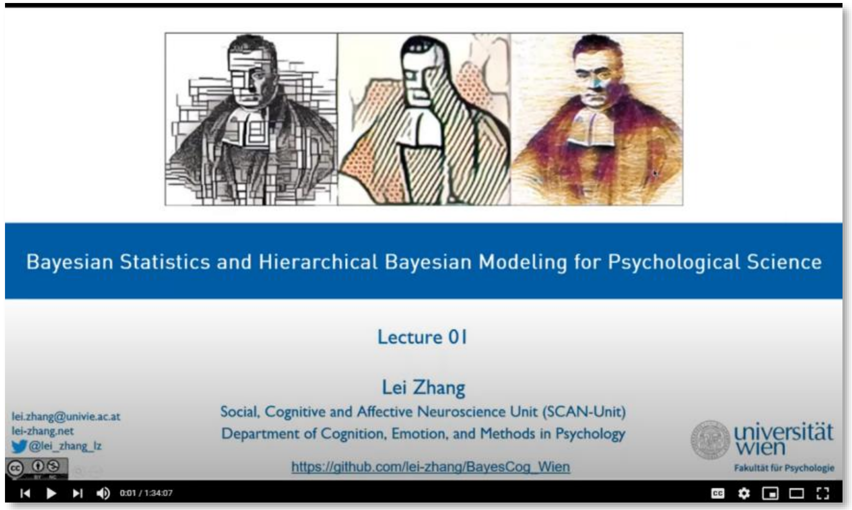
DOI 10.1162/CPSY_a_00002

hBayesDM (hierarchical Bayesian modeling of Decision-Making tasks) is a user-friendly package that offers hierarchical Bayesian analysis of various computational models on an array of decision-making tasks. hBayesDM uses Stan for Bayesian inference.









Ahn, Haines, Zhang, *Computational Psychiatry*, (2017)

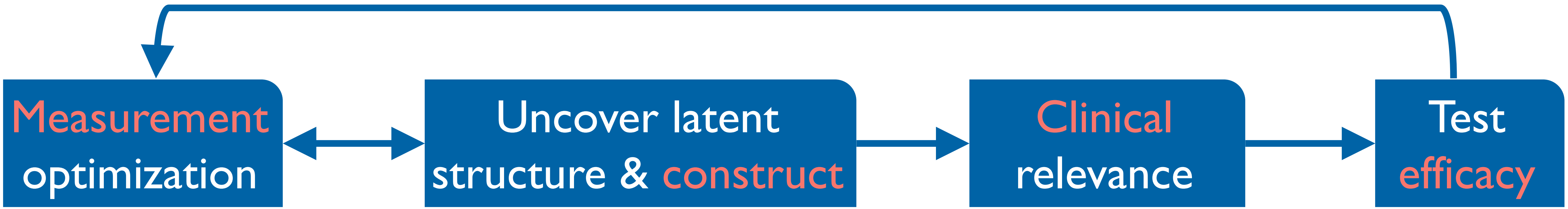
Outline

- The emergence of Computational Psychiatry (CP)
- A case study: flexible choice behavior in Autism
- hBayesDM: a toolbox for estimating hierarchical Bayesian models
- Summary

Current challenges in Computational psychiatry

- Structured initiative, laboratory → clinic?
- Test constructs within unselected samples (e.g., online/mobile/wearable)?
- Establish causality: pharmacological manipulation, (deep) brain stimulation?

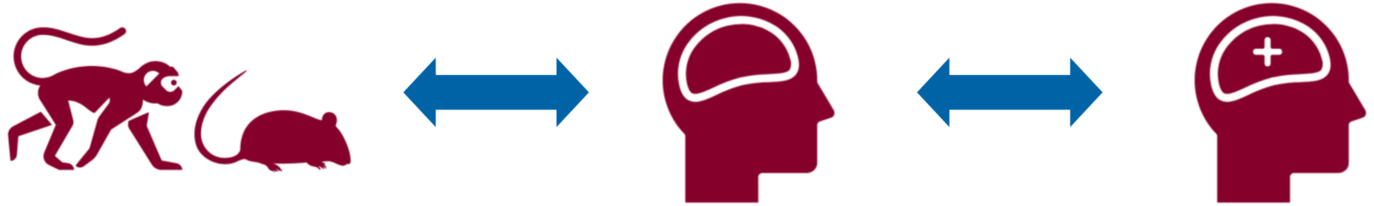
Principled Roadmap

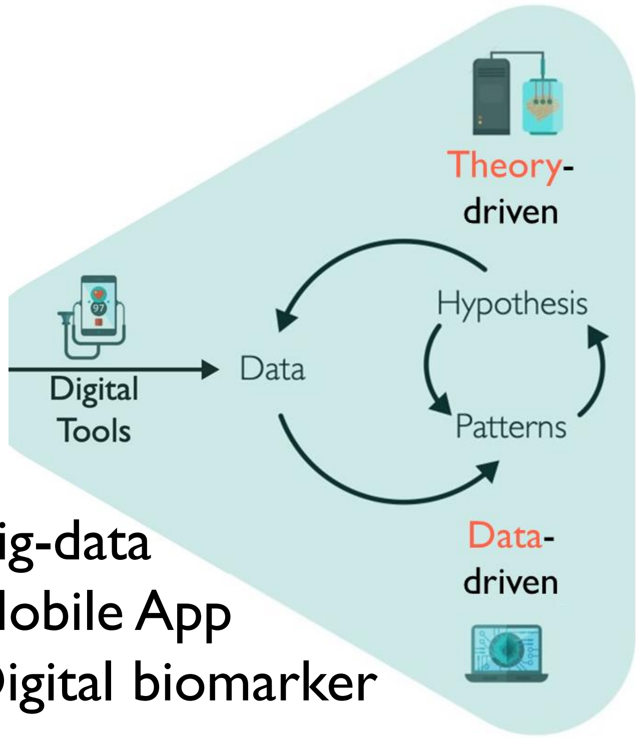


Browning et al., (2020)

Future CP

Theory-driven
+
Ethological relevance





Computation (why/goal)

Algorithm (what/rules)

Implementation (how/physical)

- Big-data
- Mobile App
- Digital biomarker

- Diagnostic
- Treatment response
- Identify sub-groups
- Speech analysis

Computational model as a link across species and cultures in CP allowing translation from fundamental discoveries to clinical practice

Summary

- CP is newly emerging and rapidly growing → embrace the opportunity!
- Computational modeling is never new → don't let it fear you!
- Improve theoretical thinking → read classic works
- Learn in pairs; no one can do everything → seek for cooperation!
- Learn to seek external help → existing packages! e.g., hBayesDM
- Be open minded, be aware of research landscape → use Twitter!

Contact

lei.zhang@univie.ac.at

https://lei-zhang.net/

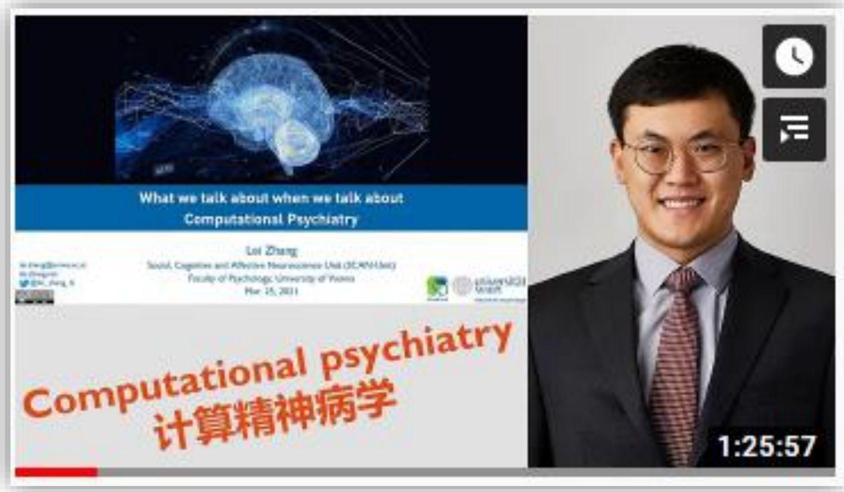
@lei_zhang_lz

@zhang-lei-44-62

@leizhang认知神经科学

@LeiZhang

@lei-zhang



SUBSCRIBE

Acknowledgement

Funding:

Bundesministerium für Bildung und Forschung

DFG

W|W|T|F

UKE HAMBURG

FFG Promoting Innovation.

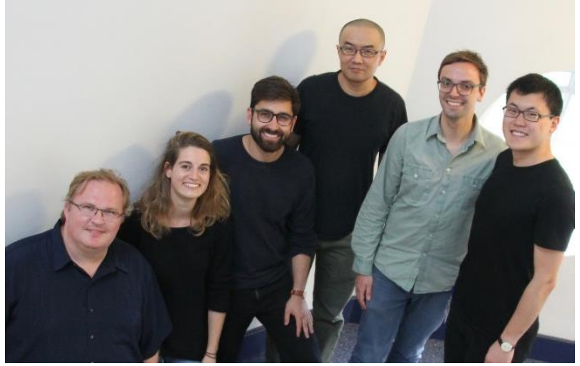
CINACS

Supervisors:

Jan Gläscher (Hamburg)
Claus Lamm (Vienna)
Chris Chatham (Roche)

Collaborators:

Woo-Young Ahn (Seoul)
Laura A. Berner (Mount Sinai)
Christian Büchel (Hamburg)
Daisy Crawley (KCL)
Hanneke den Ouden (Donders)
Jean-Claude Dreher (CNRS)
Claus C. Hilgetag (Hamburg)
Farid I. Kandil (Berlin)
Eva Loth (KCL)
Gerit Pfuhl (Tromsø)
Andrea Reiter (Würzburg)
Tobias Sommer (Hamburg)



Thank you!

@lei_zhang_lz
www.lei-zhang.net


ANY
QUESTIONS
?

Happy Computing!