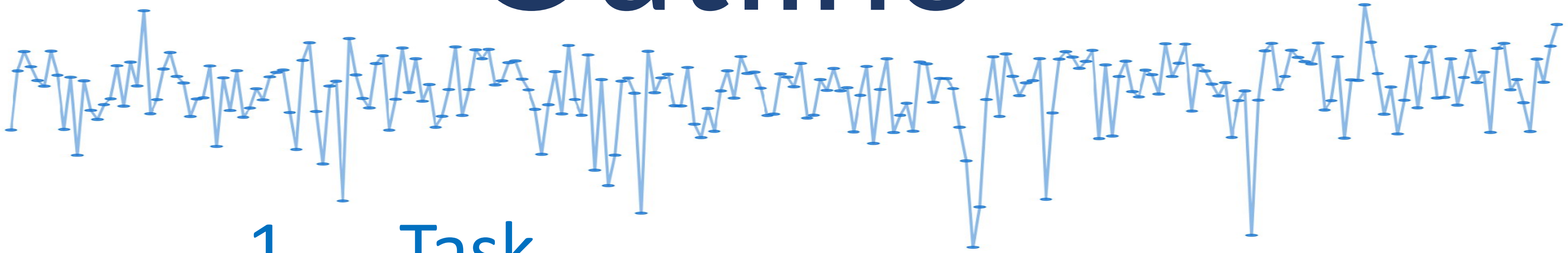
Cognitive fluctuations

How a variability perspective can offer a novel phenotype

Dr. Nicholas Judd
Lifespan Cognitive Dynamics Lab
https://njudd.com

Outline



1. Task
2. Variability's importance
3. Goals & findings
4. Future directions

Radboudumc

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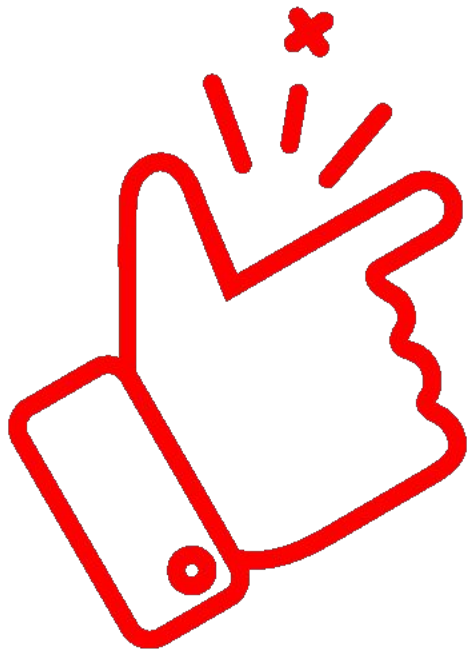
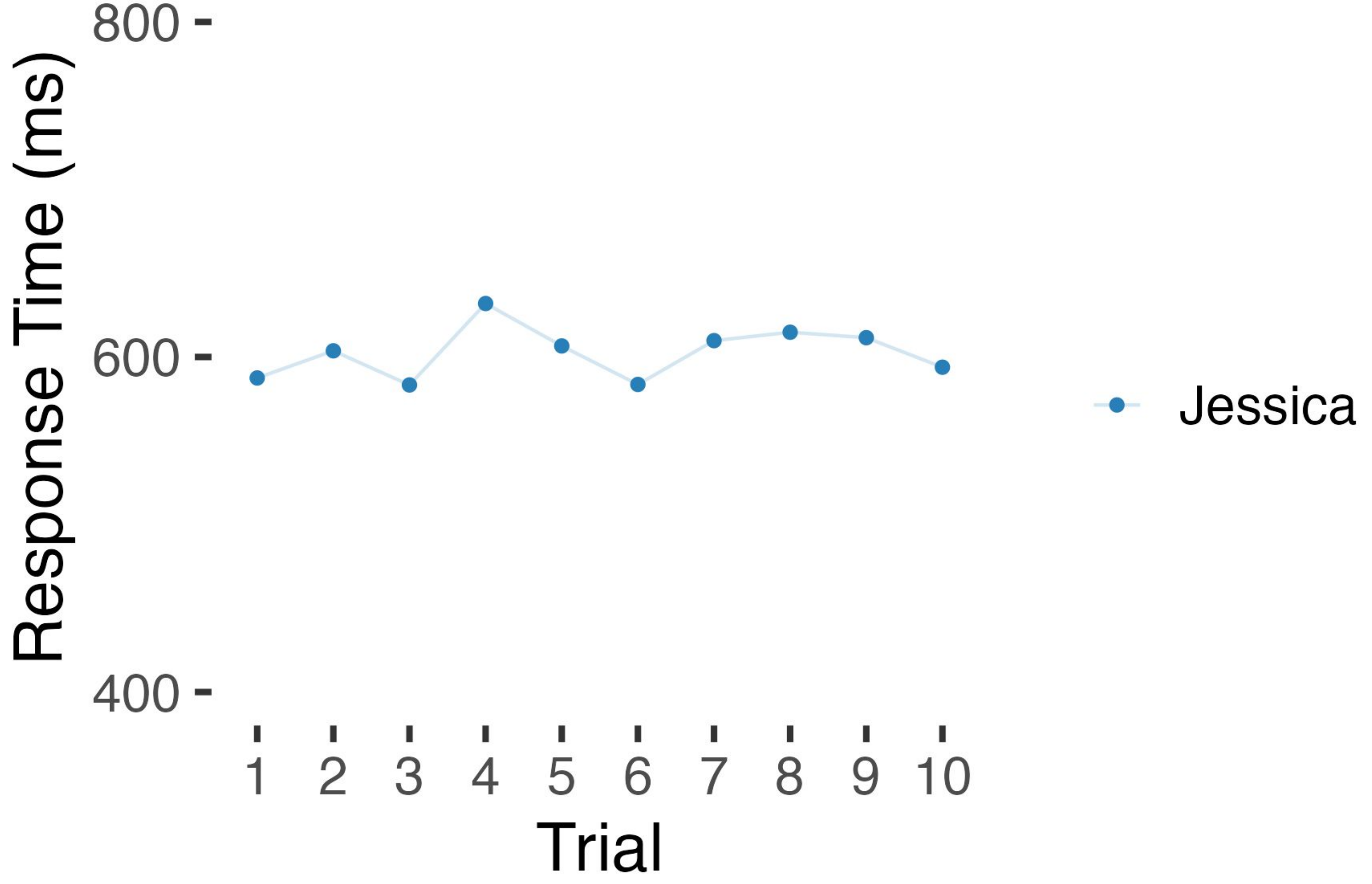
Snapping fingers task

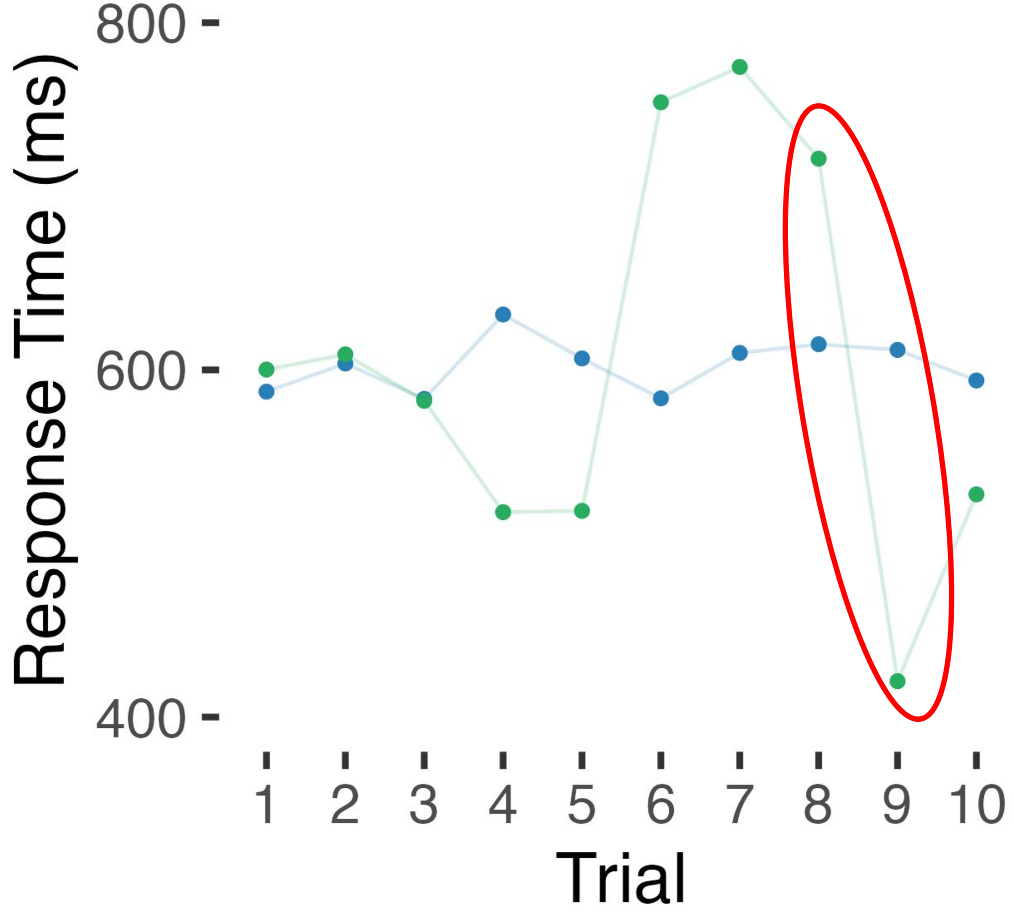
Snap your fingers



Do not respond

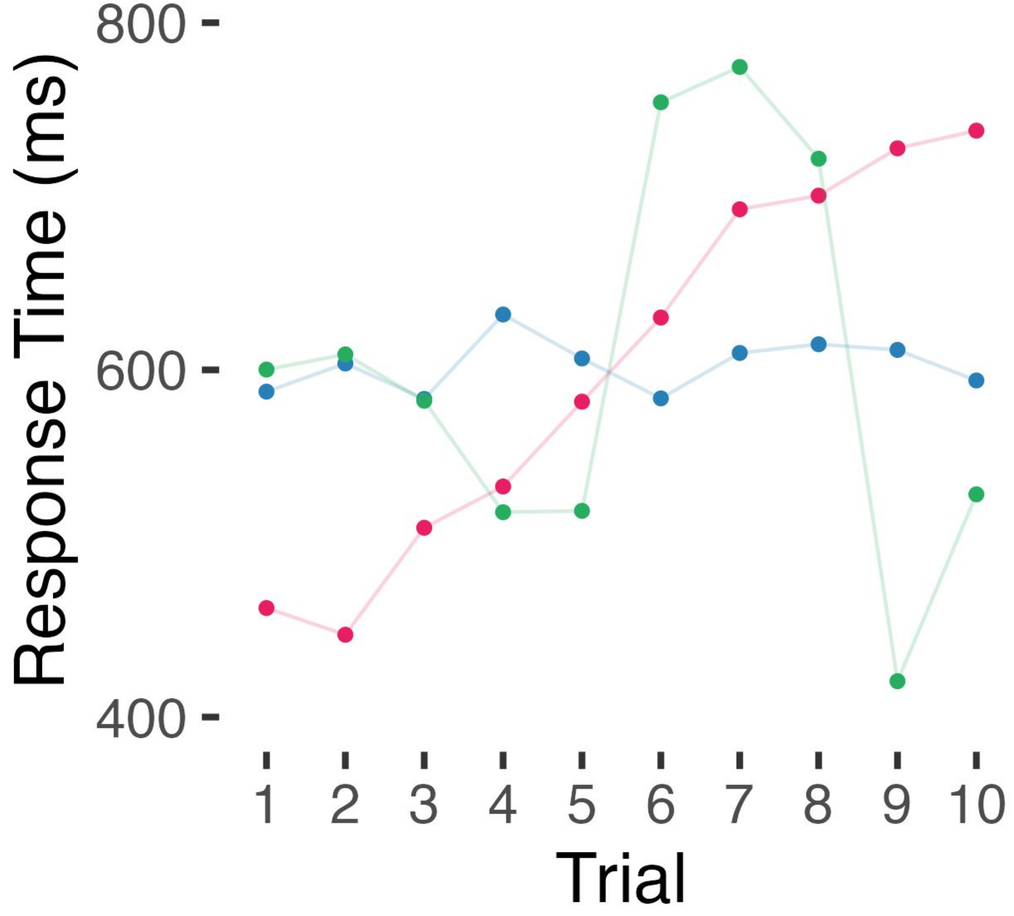


Intra-individual



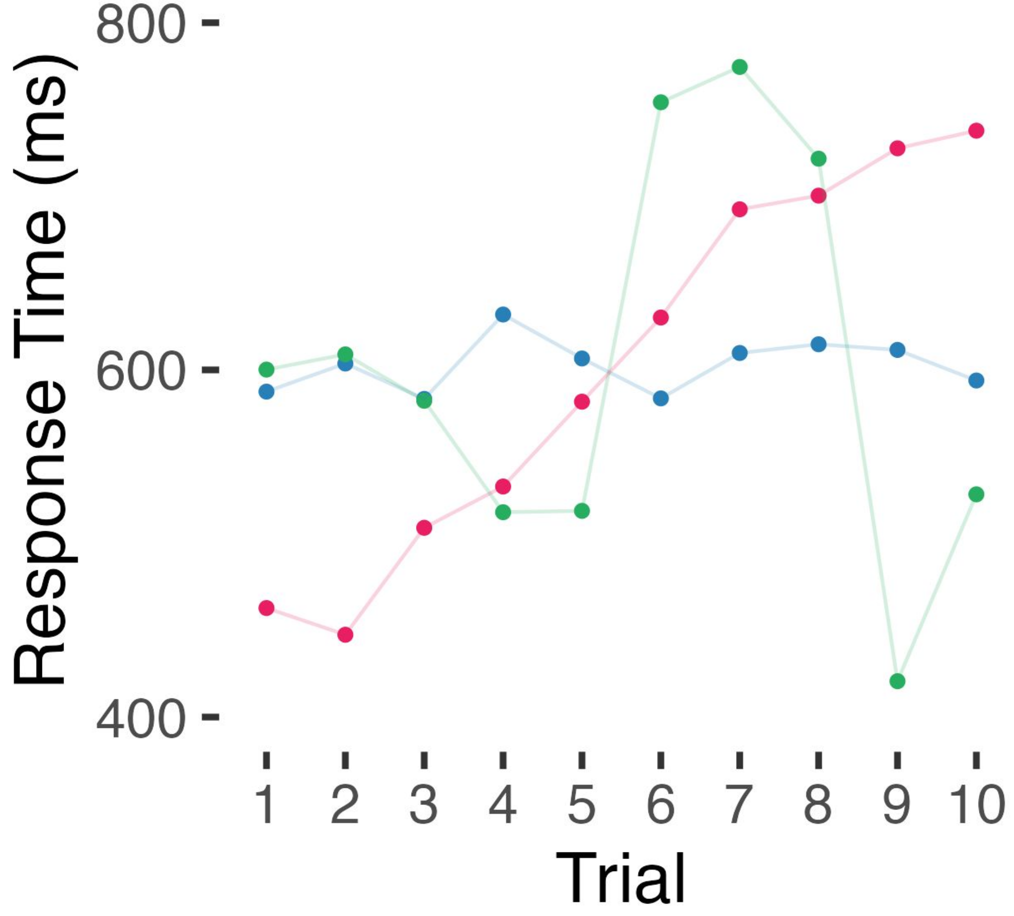
Inter-individual

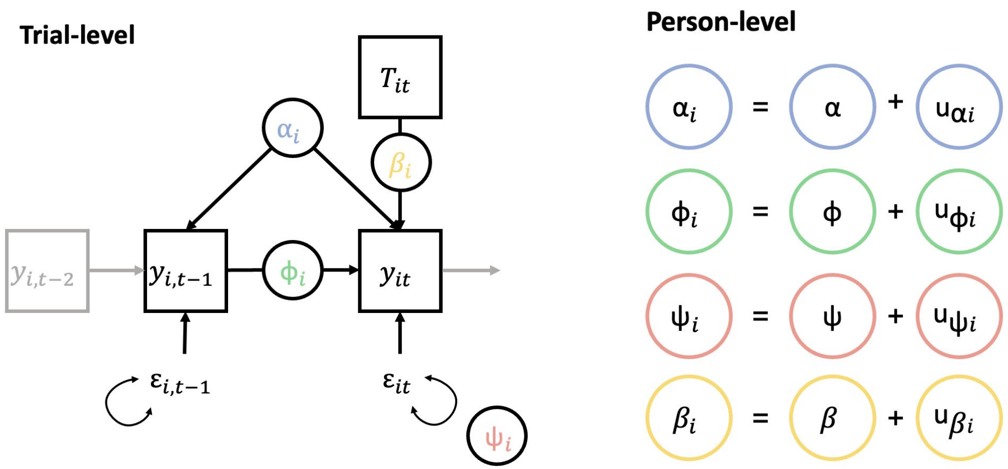
	Mean	SD
Jessica	602	15
Nick	602	115



Inter-individual

	Mean	SD
Jessica	602	15
Nick	602	115
George		

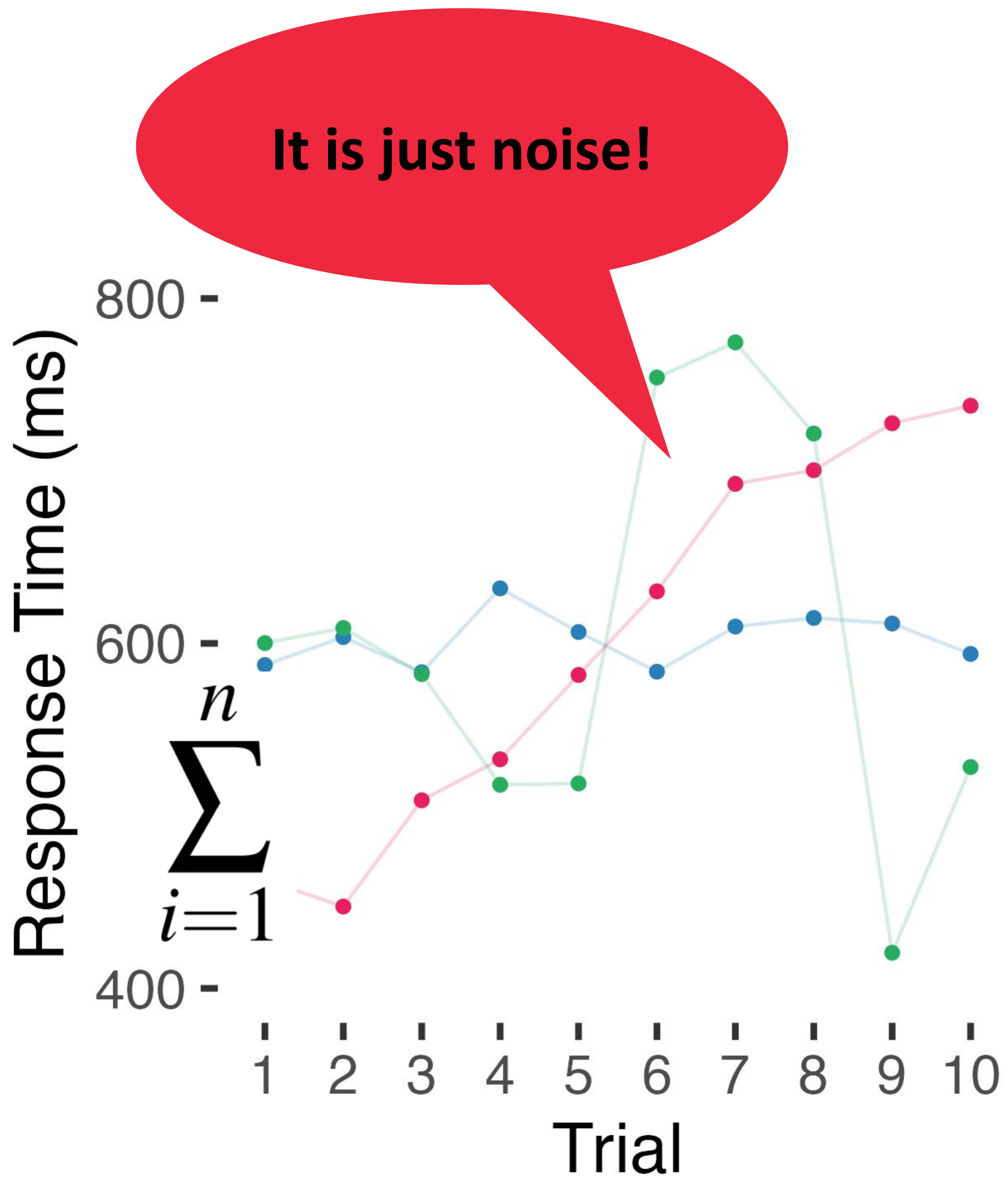




Inter-individual

	Mean	SD
Jessica	602	15
Nick	602	115
George	602	115

- Mean Performance Identical
- **big** difference in variability



Inter-individual

	Mean
Jessica	602
Nick	602
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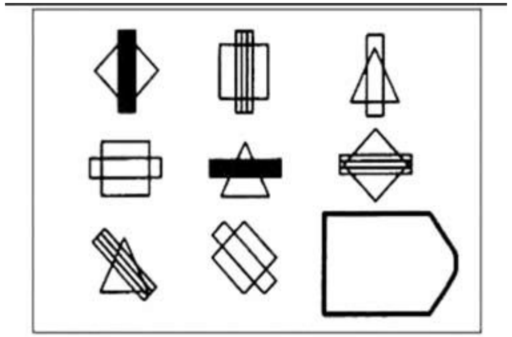
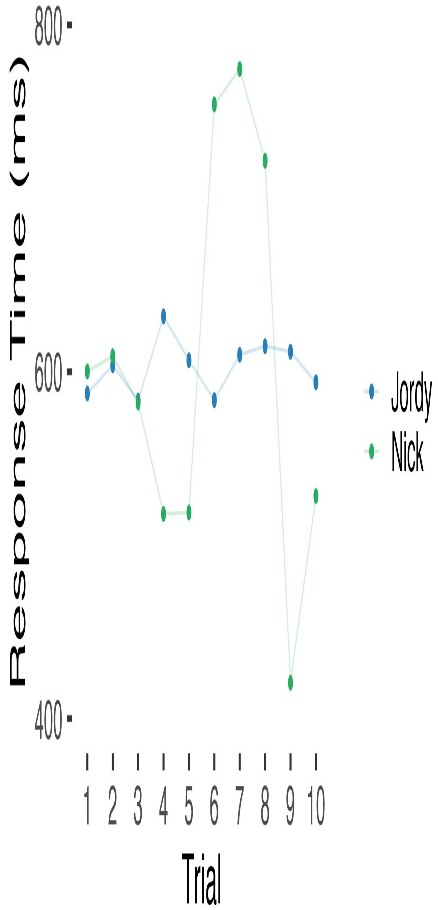


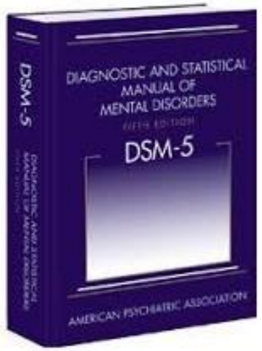
- Interindividual Differences in Mean Performance
    1. Clinical/Educational/occupational contexts

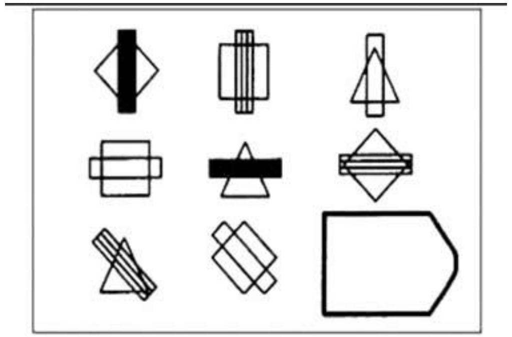
$$\sum_{i=1}^{n}$$



The ACT

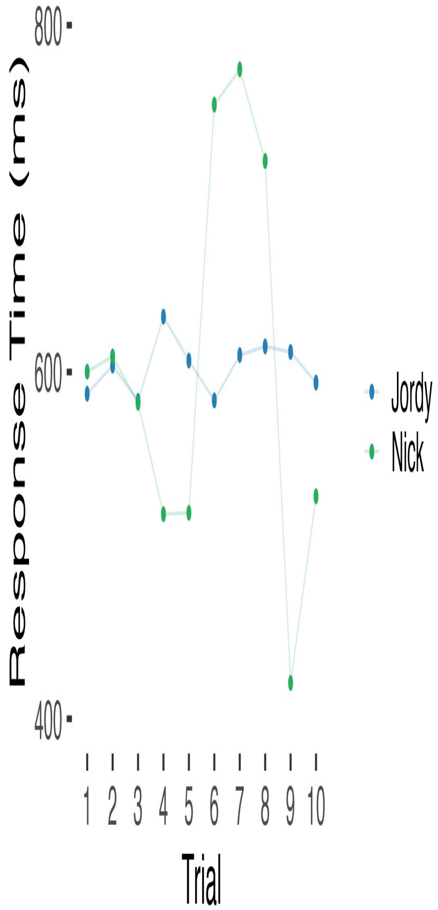
SAT

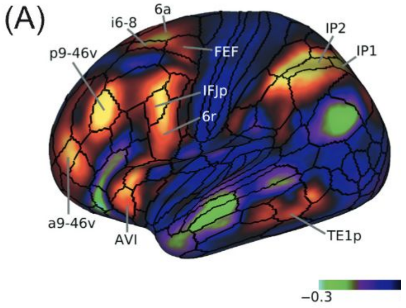




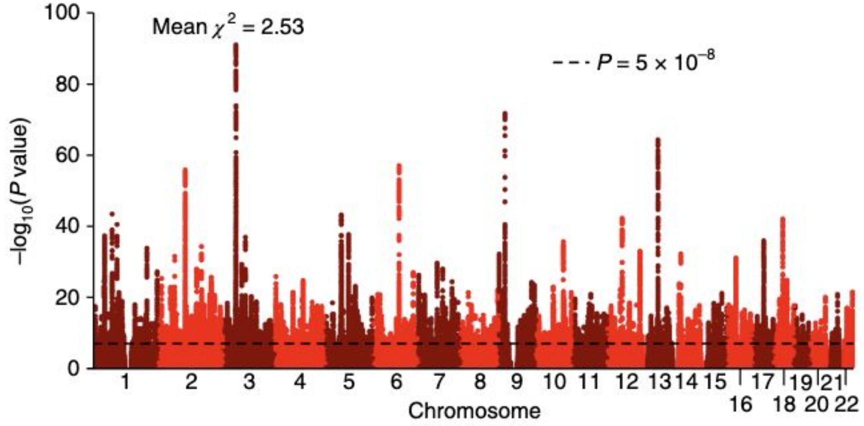
- Interindividual Differences in Mean Performance
  1. Clinical/Educational/occupational contexts
  2. Neural and genetic mechanisms

$$\sum_{i=1}^{n}$$

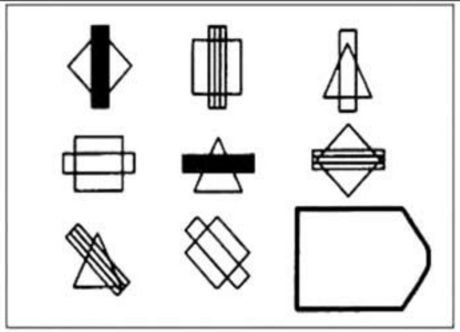




Duncan et al., 2020

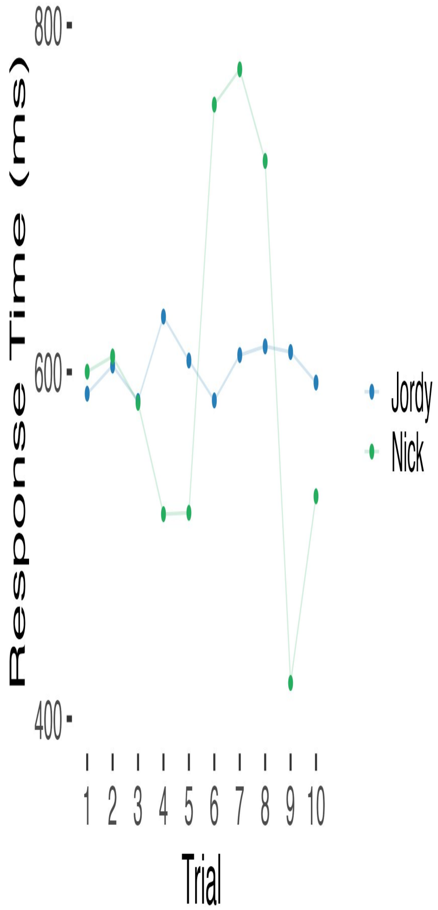


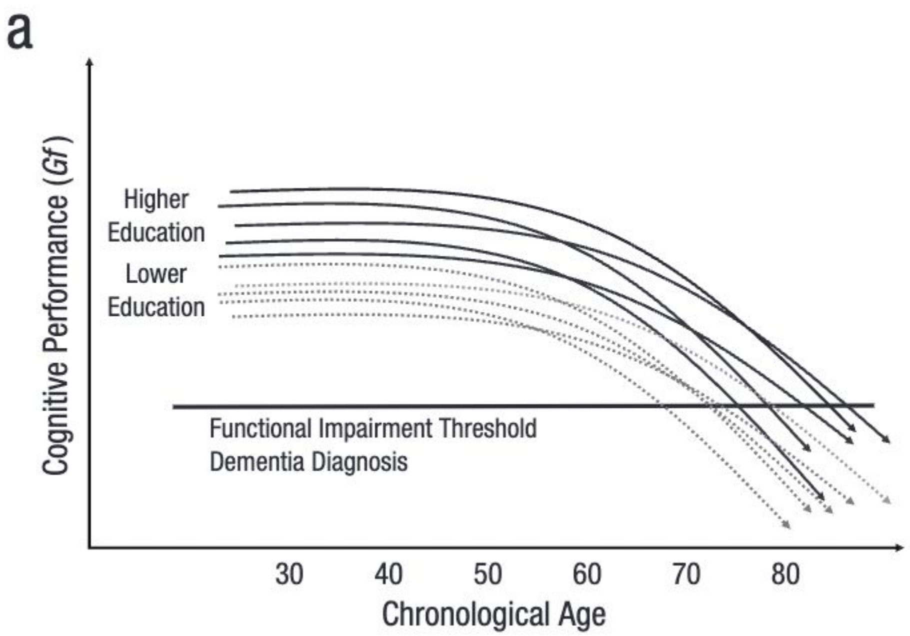
Lee et al., 2018



- Interindividual Differences in Mean Performance
  1. Clinical/Educational/occupational contexts
  2. Neural and genetic mechanisms
  3. Positively predicts important outcomes

$$\sum_{i=1}^{n}$$





Tucker-Drob 2019

But, wait a second...

…what about these big differences in variability we saw?

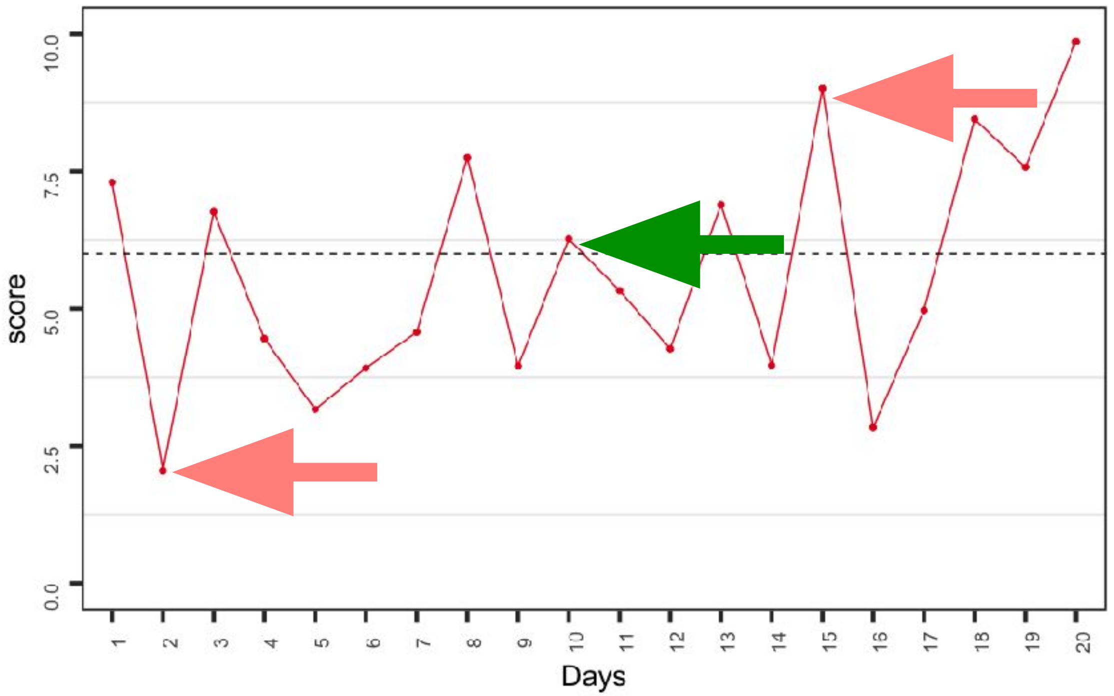
But, wait a second...

…what about these big differences in variability we saw?

And are they meaningful...?

Why is variability important?

- A neglected source of individual differences
- Variability can lead to mis-stratification with lifelong consequences
- Variability is likely a sensitive, early marker of atypical development

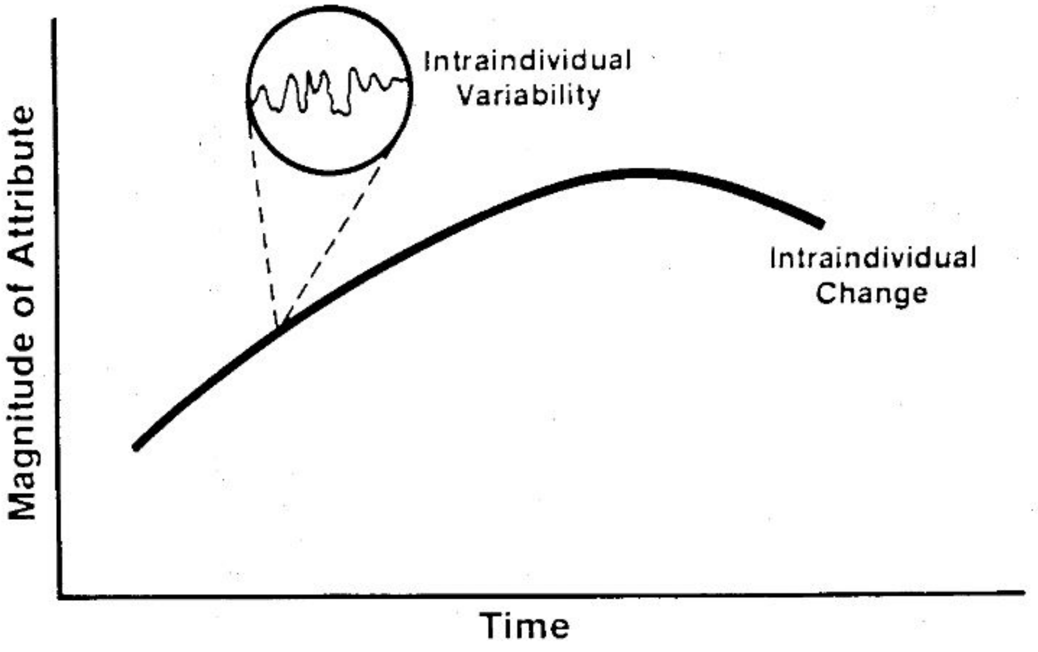


Why is variability important?

- An urgent need to better understand *adaptive* versus *maladaptive* variability
- Crucial function in learning
    - Songbirds
    - Humans (Wu et al., 2013)

The Warp and the Woof of the Developmental Fabric

John R. Nesselroade
The Pennsylvania State University



general, much less variability in behavior than do organisms. Indeed, variability, inconsistency, and specific unpredictability of behavior have long been recognized as the chief molar distinctions between organisms and inorganic machines. Clearly a character-

Patterns of Change: Measurement in Relation to State-Dimension, Trait Change, Lability, and Process Concepts

RAYMOND B. CATTELL
University of Illinois

Fiske & Rice, 1955

INTRA-INDIVIDUAL RESPONSE VARIABILITY[1]

DONALD W. FISKE AND LAURA RICE[2,3]
University of Chicago

The problem of intra-individual variability has not been subjected to systematic conceptualization.

FINAL REPORT

SHORT PERIOD FLUCTUATIONS IN INTELLIGENCE

"unity" and what is meant by "functional". The results illustrated how fluid intelligence (as well as other attributes of intellectual test behavior) varies functionally within persons and also represents a stable pattern of performances that distinguishes one person from another. This kind of finding could have considerable value in several fields of psychology.

Why has variability ignored?

1. Limits in data

2. Limits on quantification

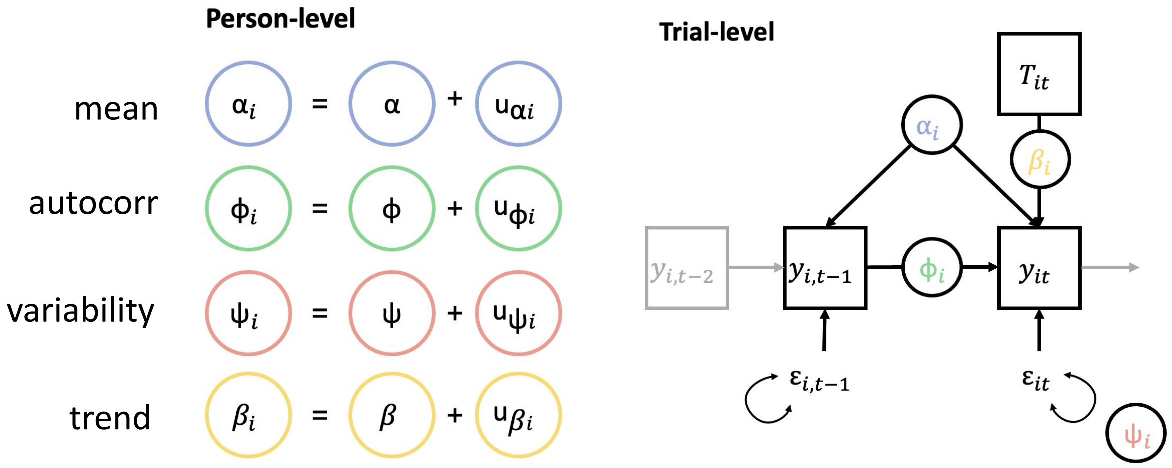
Why has variability ignored?

1. Limits in data

   - Dense, time series data

2. Limits on quantification

   - Novel modeling techniques (Dynamic SEM)



McNeish & Hamaker, 2020

Aims:
3 fundamental properties of cognitive variability

1. Ubiquity
   do we find cognitive variability in each task?
2. Structure
   how are individual differences in variability across tasks related?
3. Discrimination
   is variability a distinct concept from mean performance?

Judd & Klingberg, 2021

Methods – **Sample**

- A math training app
- 6-8 year old children (n = 2608)
- 11 tasks with 7,204,127 trials

Mathematics (~50%)	Working Memory (~20%)
Rotation (~20%)	Non-verbal reasoning (~10%)

Methods – **Sample**

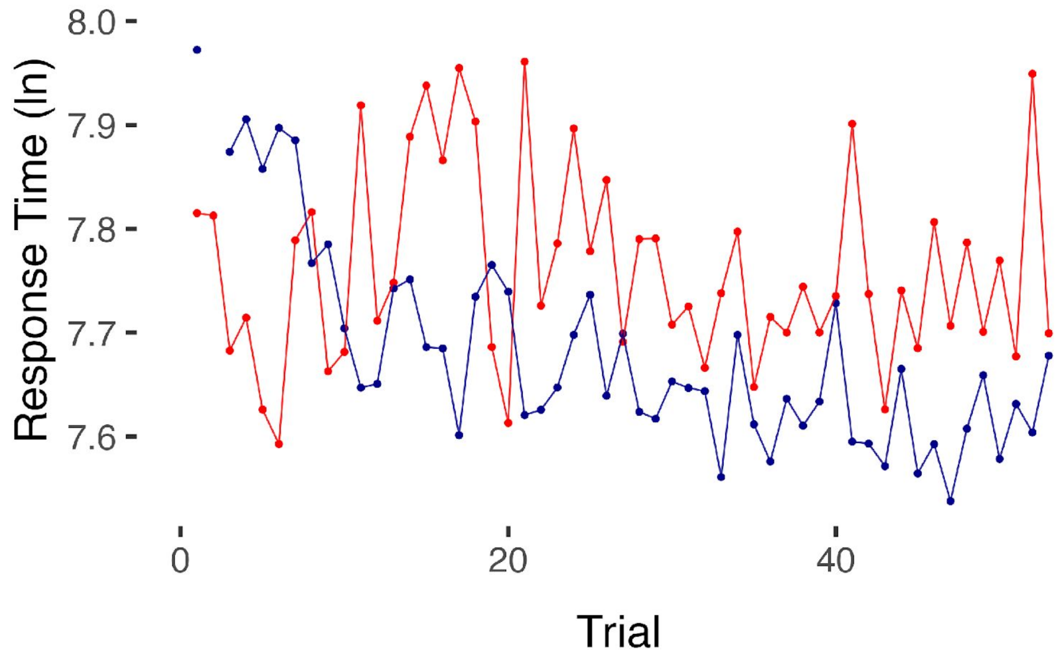
Mathematics (~50%)	Working Memory (~20%)
Rotation (~20%)	Non-verbal reasoning (~10%)

“tangram”

Methods – **Sample**

- Cognitive Variability = Response time of correct trials
- Mean performance = Average level of a child

$$\psi_i = \psi + u_{\psi i}$$



Results – **Ubiquity**

- Model fit comparison (dDIC)
- Found meaningful inter-individual differences in intra-individual variability across <u>all 11 tasks</u>

Model 1 (full model)

$$\alpha_i = \alpha + u_{\alpha i}$$
$$\phi_i = \phi + u_{\phi i}$$
$$\psi_i = \psi + u_{\psi i}$$
$$\beta_i = \beta + u_{\beta i}$$

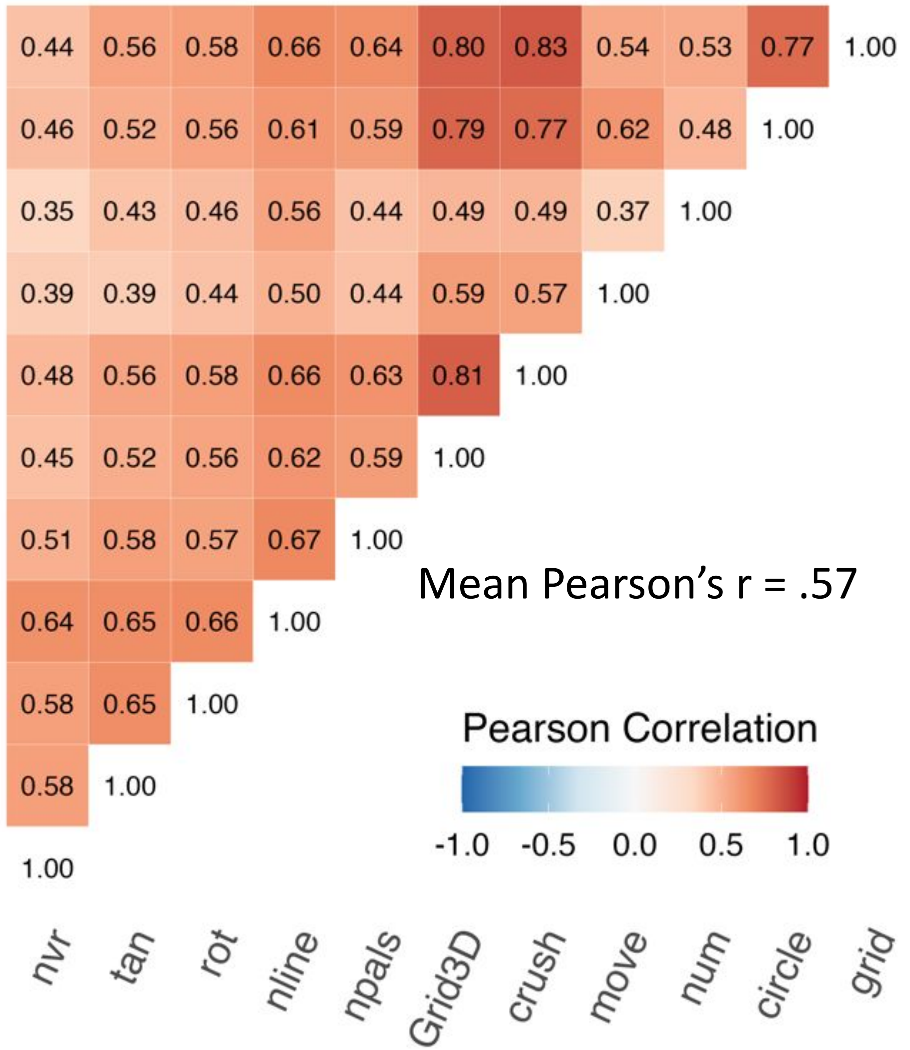
Model 2 (no variability parameter)

$$\alpha_i = \alpha + u_{\alpha i}$$
$$\phi_i = \phi + u_{\phi i}$$
$$\psi_i = \psi + \cancel{u_{\psi i}}$$
$$\beta_i = \beta + u_{\beta i}$$

Results – **Structure**

Cognitive variability

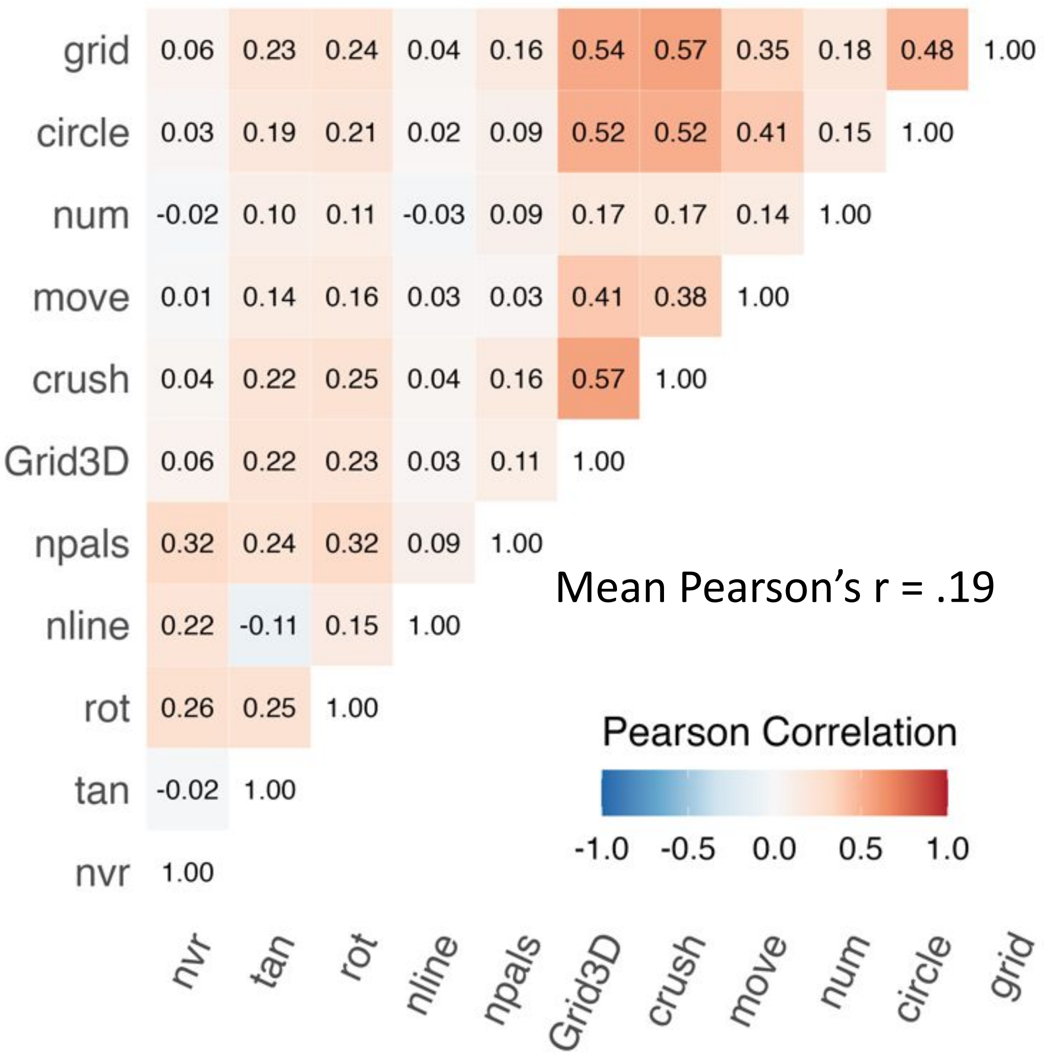
Mean performance



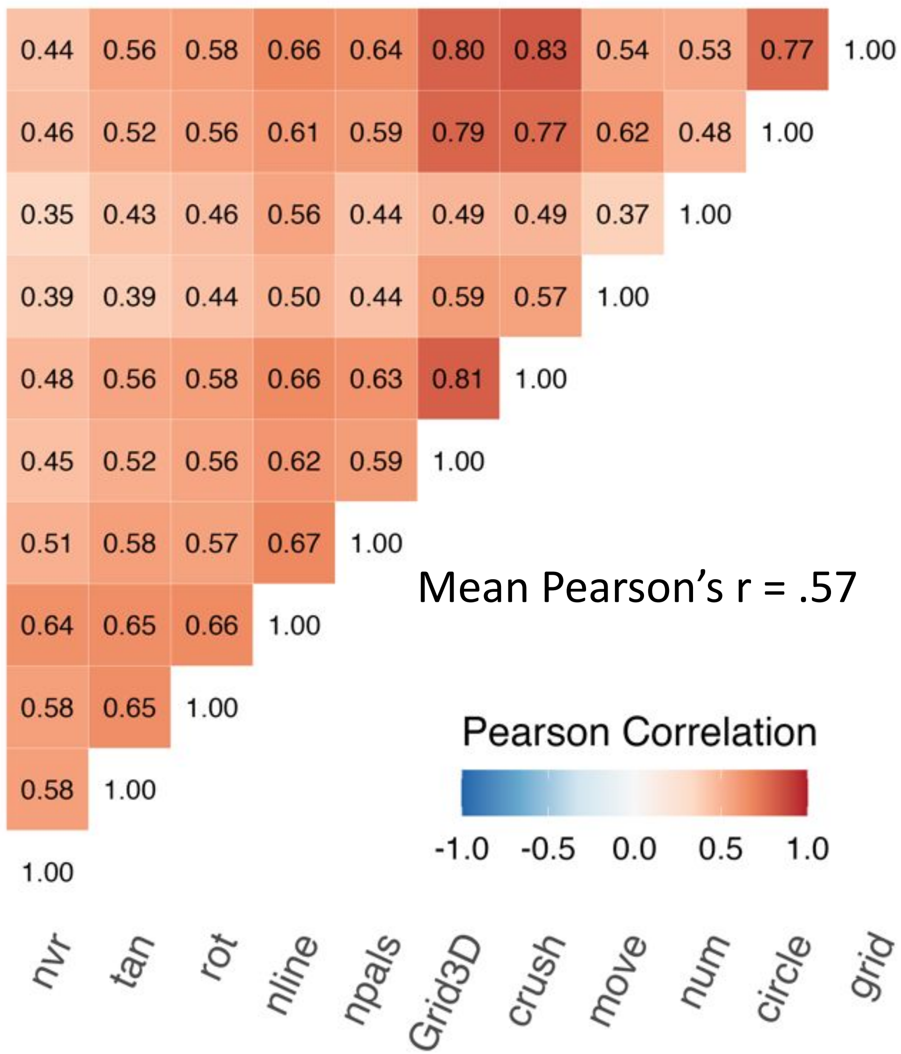
Mean Pearson’s r = .57

Results – **Structure**

Cognitive variability

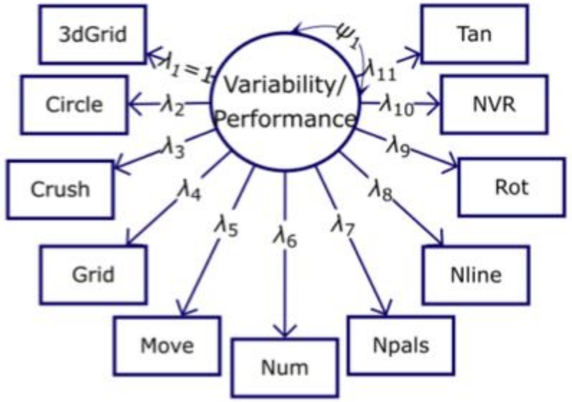


Mean performance



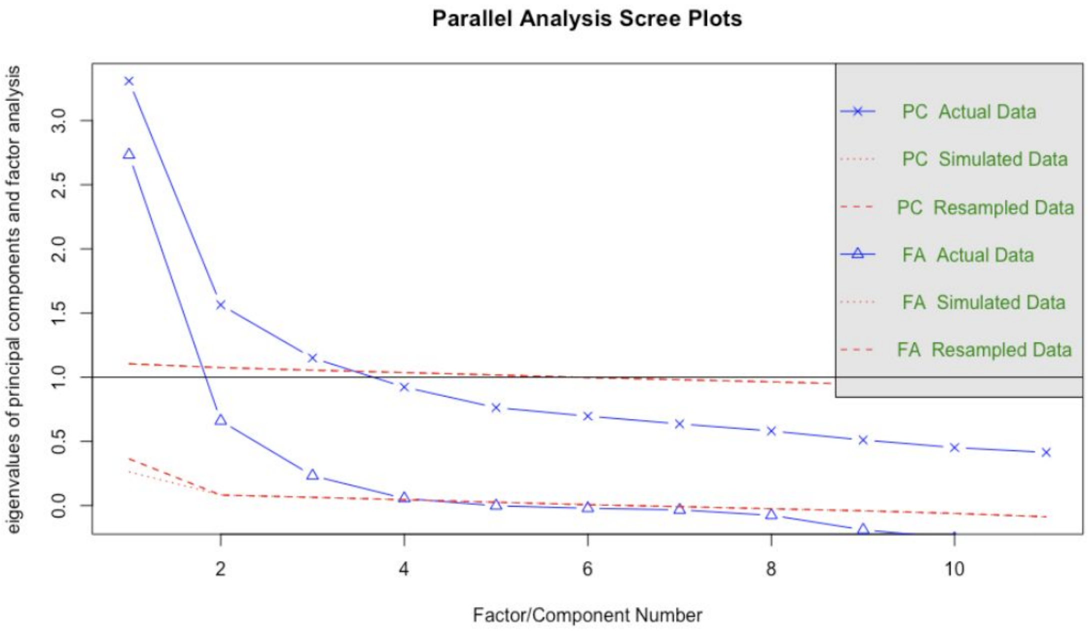
Results – **Structure**

- We used confirmatory factor analysis
- None of our *a priori* models fit variability well



Shifted to an exploratory factor analysis

- 3-factor solution

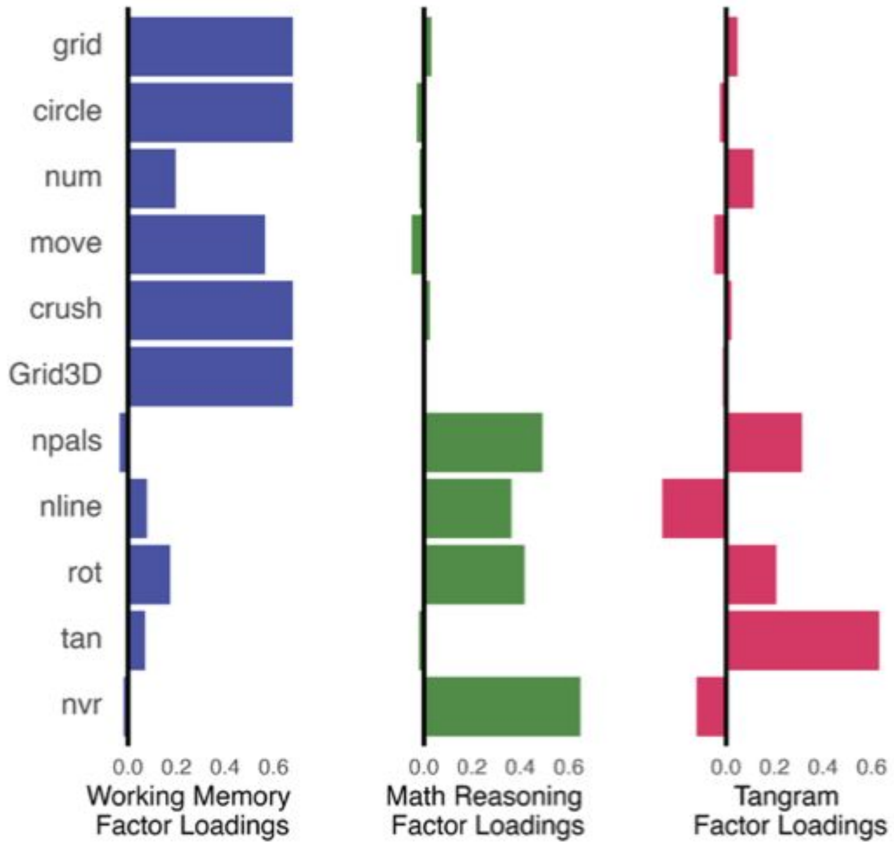


Results – **Structure**

- We used confirmatory factor analysis
- None of our *a priori* models fit variability well

Shifted to an exploratory factor analysis

- 3-factor solution
  1. Working memory (22%)
  2. Math-reasoning (9%)
  3. Tangram (6%)



Results – **Discrimination**

- Unique from mean performance
  1. The within-task DSEM parameters

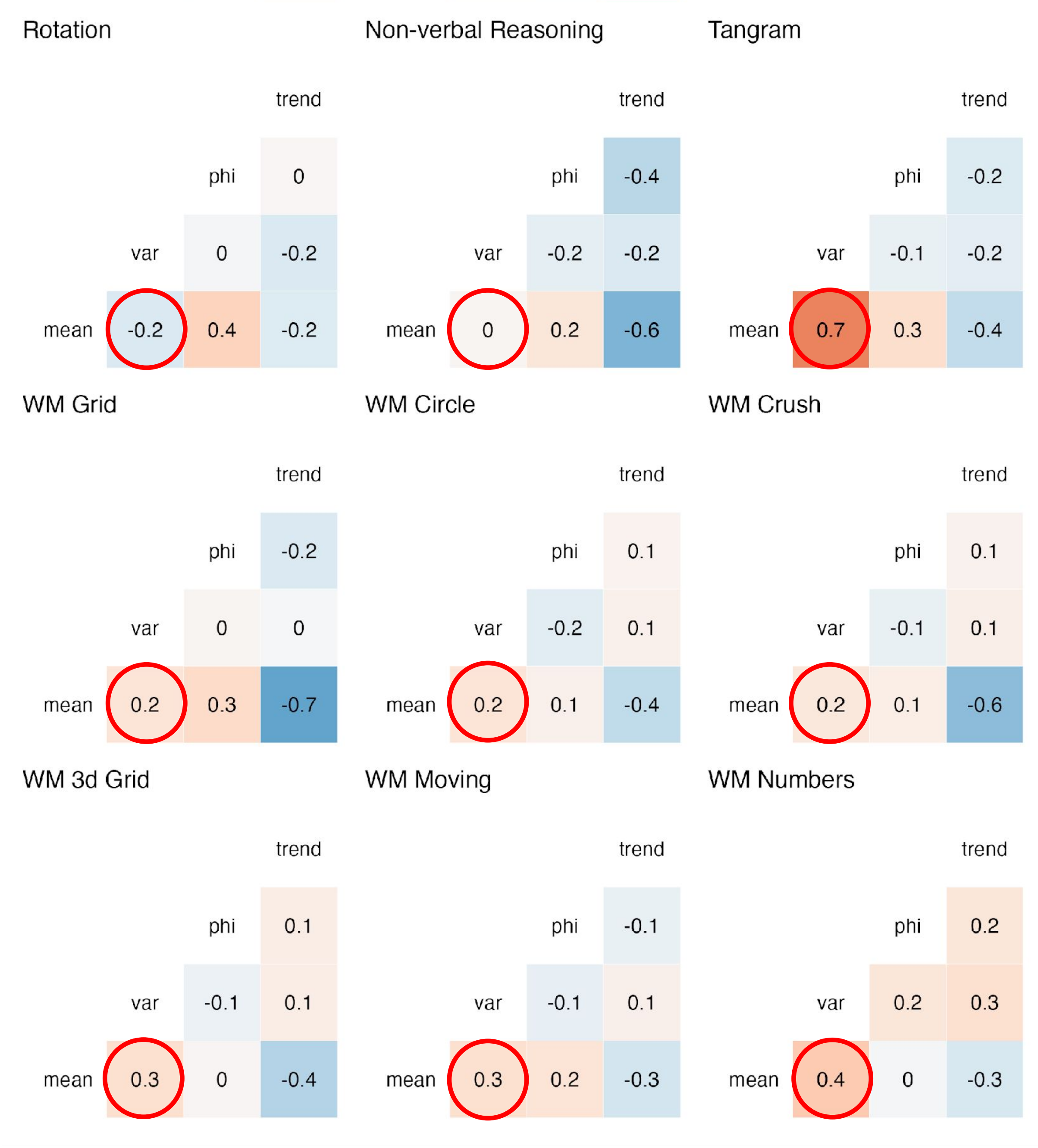
Person-level

mean $\alpha_i = \alpha + u_{\alpha i}$

phi $\phi_i = \phi + u_{\phi i}$

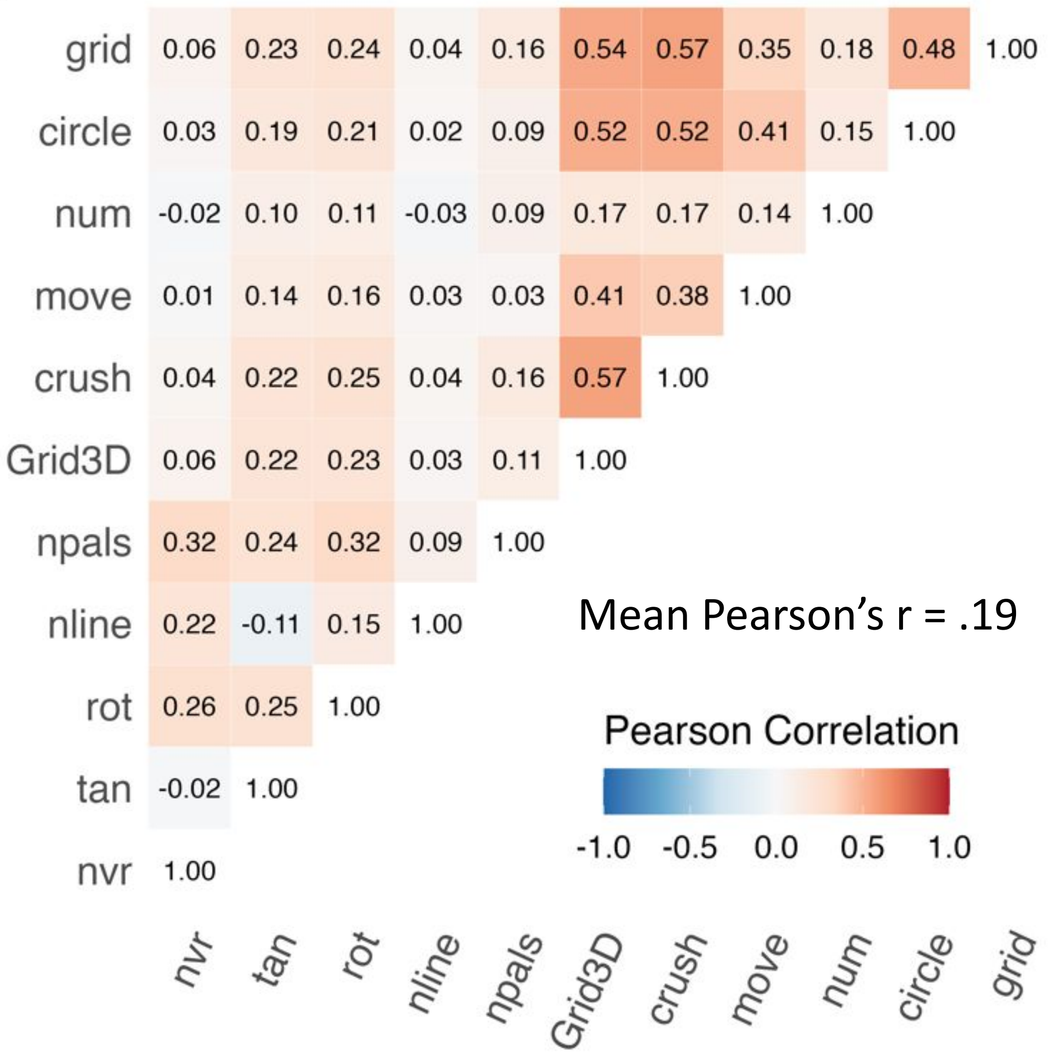
var $\psi_i = \psi + u_{\psi i}$

trend $\psi_i = \psi + u_{\psi i}$



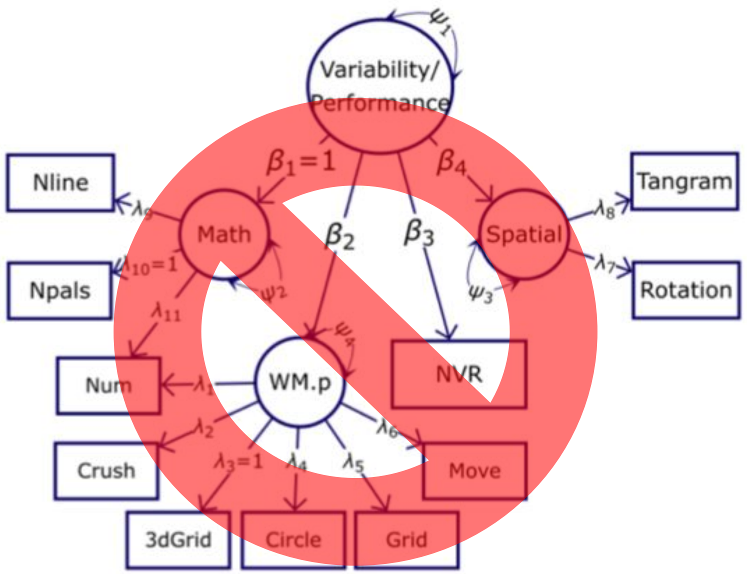
Results – **Discrimination**

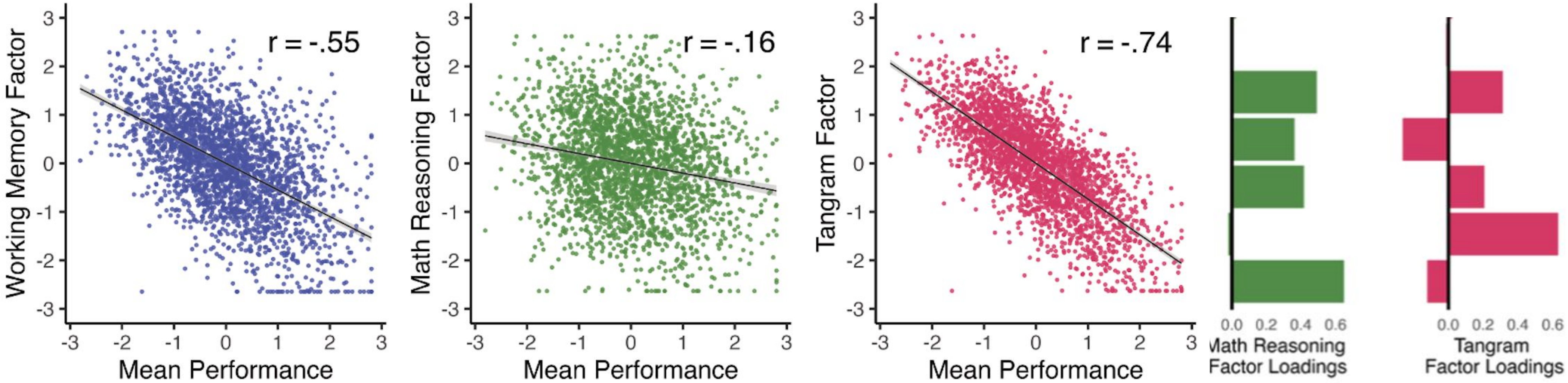
- Unique from mean performance
  1. The within-task DSEM parameters
  2. Weak correlations across tasks



Results – **Discrimination**

- Unique from mean performance
  1. The within-task DSEM parameters
  2. Weak correlations across tasks
  3. Factor structure
  4. EFA correlations with mean performance





Take home messages

1. There is *meaningful* interindividual variability across all tasks studied
2. Cognitive variability has a unique structure
3. Distinct from mean performance

Take home messages

1. There is *meaningful* interindividual variability across all tasks studied
2. Cognitive variability has a unique structure
3. Distinct from mean performance

It is **not** just noise!!!

It is **not** the same signal!

Take home messages

1. There is *meaningful* interindividual variability across all tasks studied
2. Cognitive variability has a unique structure
3. Distinct from mean performance

- We are very limited in our ability to figure out exactly *what* these task-specific factors are
- Specific age range with swedish sample

Interindividual Differences in Cognitive Variability Are Ubiquitous and Distinct From Mean Performance in a Battery of Eleven Tasks

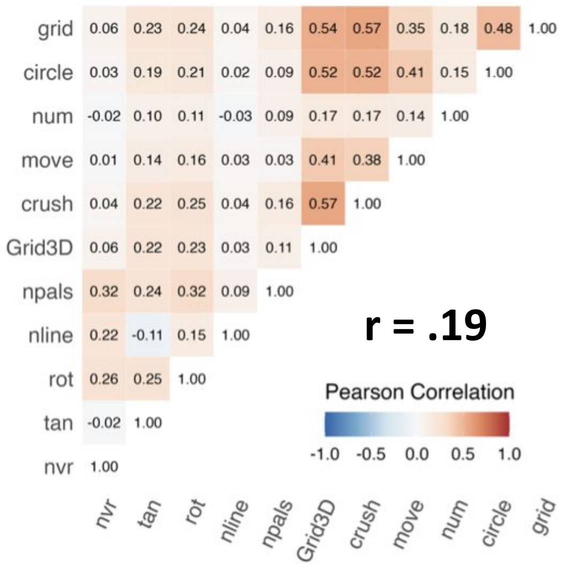
NICHOLAS JUDD
MICHAEL ARISTODEMOU
TORKEL KLINGBERG
ROGIER KIEVIT

journal of cognition

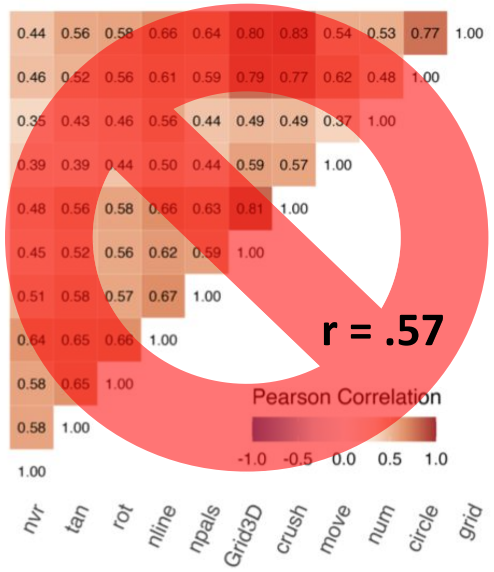
Future – Avenues

- Potentially a phenotypically differentiating tool
- Identifying influences of global and task-specific causes
- How the mean relates to variability
  - Learning processes
  - Explore vs Exploit

Variability



Mean

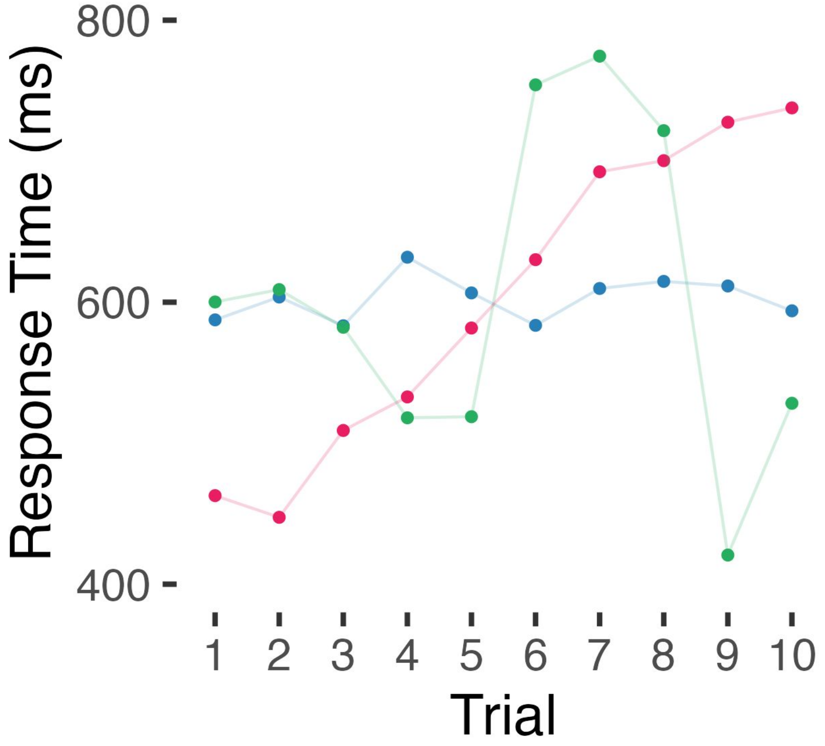


why psychometrics is important to me

- Bridge from theory to estimand
- It get's us closer to what we want to measure
- Which get's us a *bit closer* to 'the truth'

It is a fundamental way to make your empirical science better.

	Mean	SD
Jessica	602	15
Nick	602	115
George	602	115



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Thank you for your attention

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@njudd.com

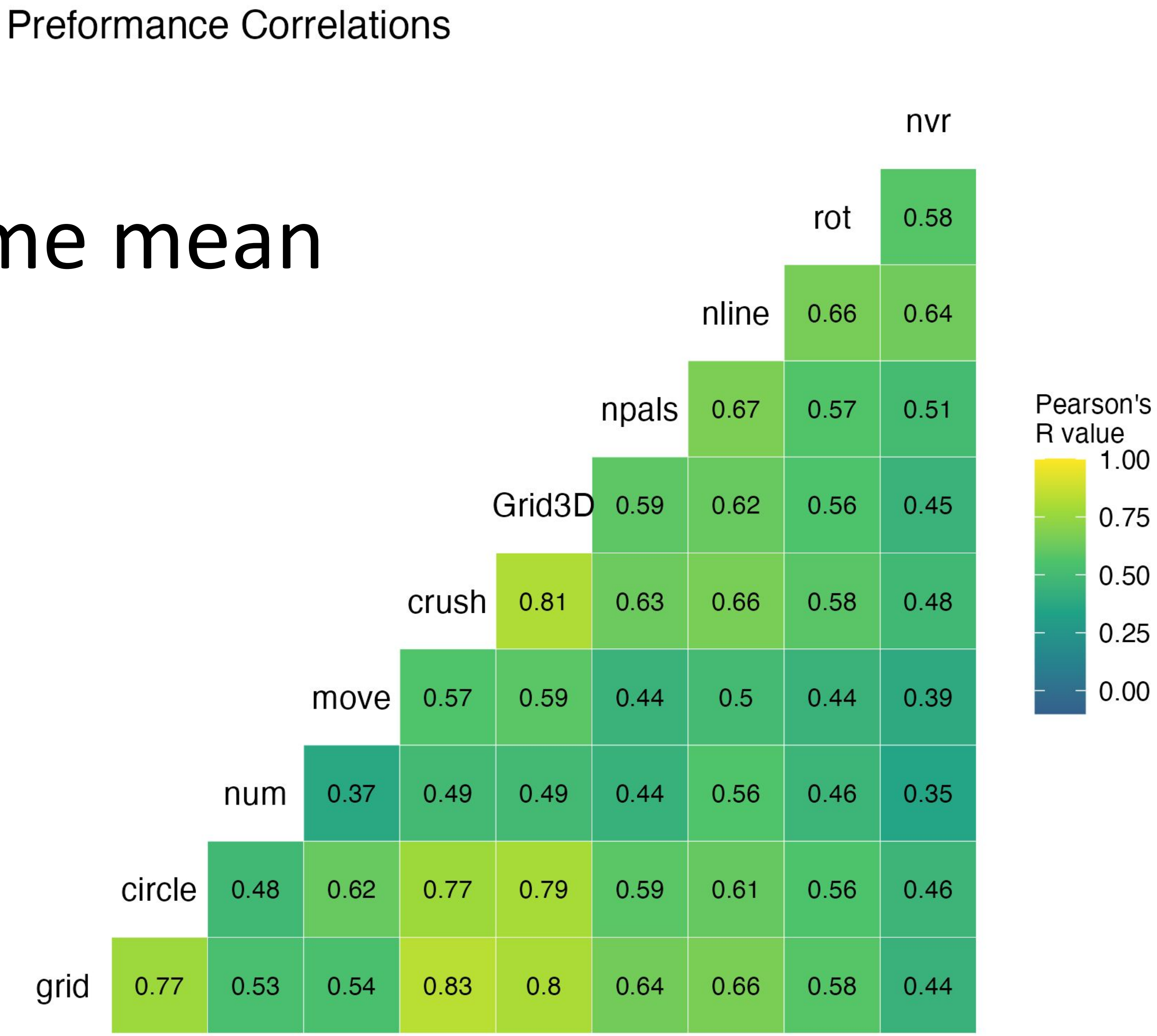
https://njudd.com/cognitive-fluctuations/

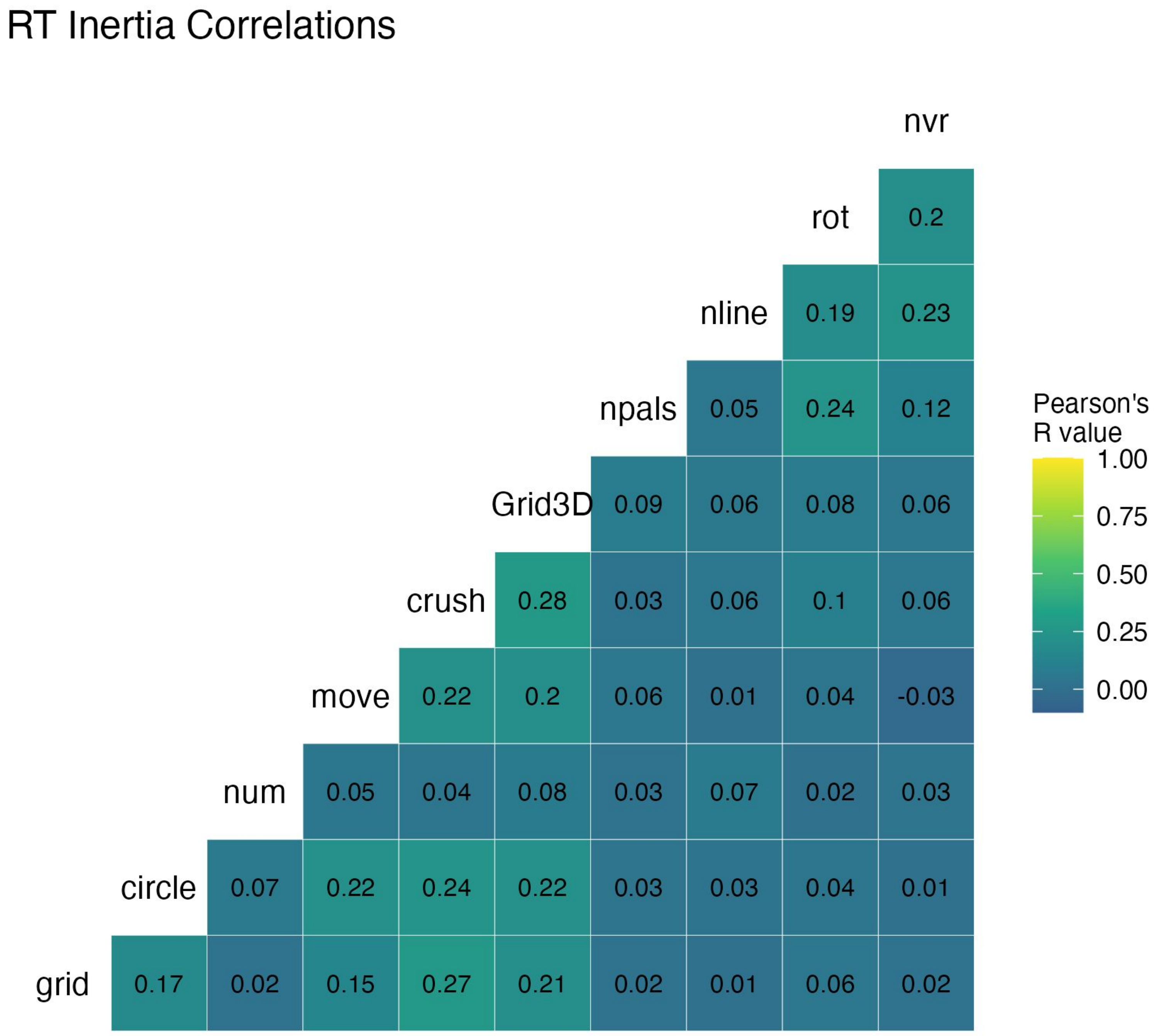
https://lifespancognitivedynamics.com

Rogier Kievit | Jessica Schaaf | Ilse Coolen | Jordy van Langen | Eleni Zimianiti | Michael Aristodemou | Lea Michel | Sam Parsons | Nick Judd | Emma Meeussen | Sophie Hofman

Bonus slides

Response time mean




RT Inertia Correlations
nvr
rot 0.2
nline 0.19 0.23
npals 0.05 0.24 0.12
Grid3D 0.09 0.06 0.08 0.06
crush 0.28 0.03 0.06 0.1 0.06
move 0.22 0.2 0.06 0.01 0.04 -0.03
num 0.05 0.04 0.08 0.03 0.07 0.02 0.03
circle 0.07 0.22 0.24 0.22 0.03 0.03 0.04 0.01
grid 0.17 0.02 0.15 0.27 0.21 0.02 0.01 0.06 0.02
Pearson's
R value
1.00
0.75
0.50
0.25
0.00

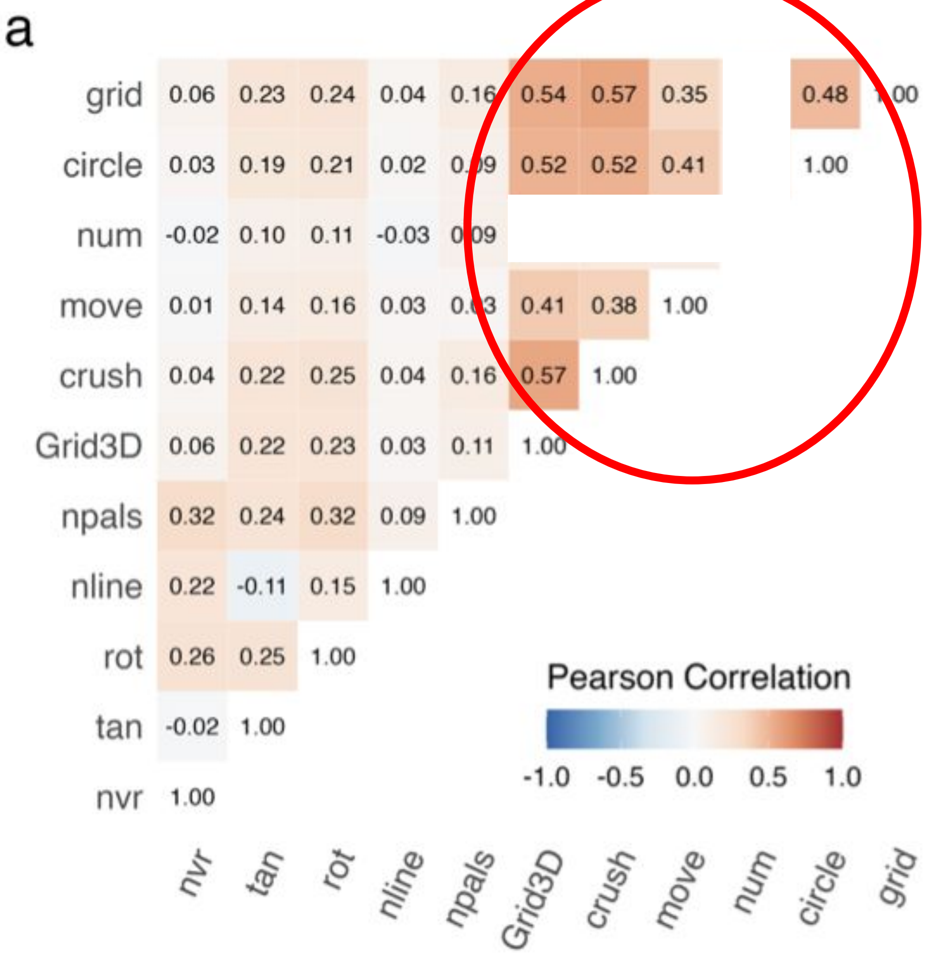
Reliability

- The variability parameter was also reliable within tasks (>.9)

Supplementary Table 2: Trial variance reliability estimations.

Task	# subs	# Trials	Avg # trials	tv_rel.5	tv_rel.7	tv_rel.9
WM_3dgrid (3DGrid)	2608	203738	78.12	0.981	0.988	0.992
WM_circle (circle)	2608	155878	59.77	0.978	0.986	0.99
WM_crush (crush)	2608	243511	93.37	0.985	0.991	0.995
WM_grid (grid)	2608	430708	165.15	0.99	0.994	0.996
WM_moving (move)	2569	85640	33.34	0.971	0.98	0.986
WM_numbers (num)	2591	98300	37.94	0.952	0.972	0.984
Npals	2608	2398463	919.66	0.961	0.981	0.992
Numberline (nline)	2608	1833909	703.19	0.933	0.966	0.981
Non-verbal reasoning (nvr)	2608	548101	210.16	0.761	0.865	0.917
Rotation (rot)	2608	1032751	395.99	0.929	0.964	0.983
Tangram (tan)	2608	173128	66.38	0.593	0.76	0.858

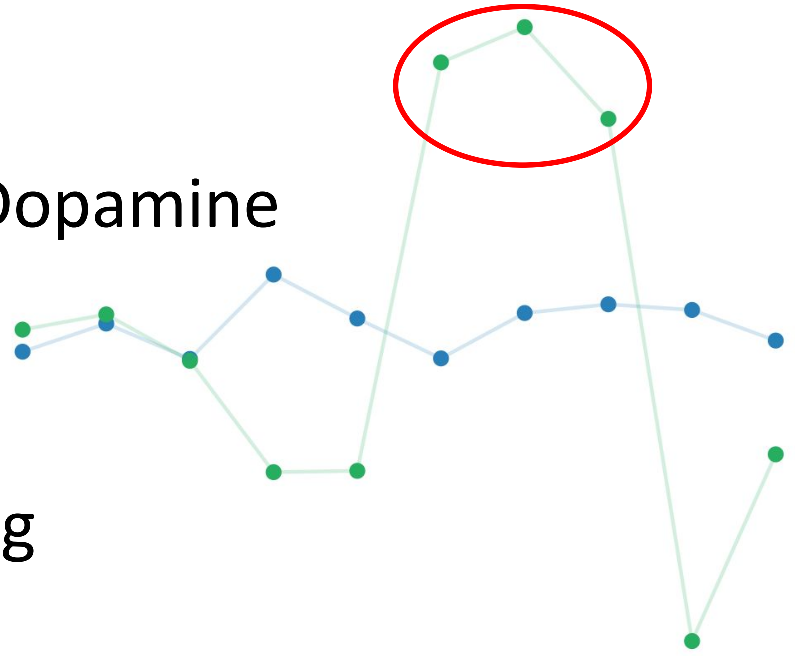
(Du & Wang, 2018)



What causes of variability?

Global causes

- (in)Attention
- Norepinephrine/Dopamine
- Fatigue
- Affect
- Sensory processing



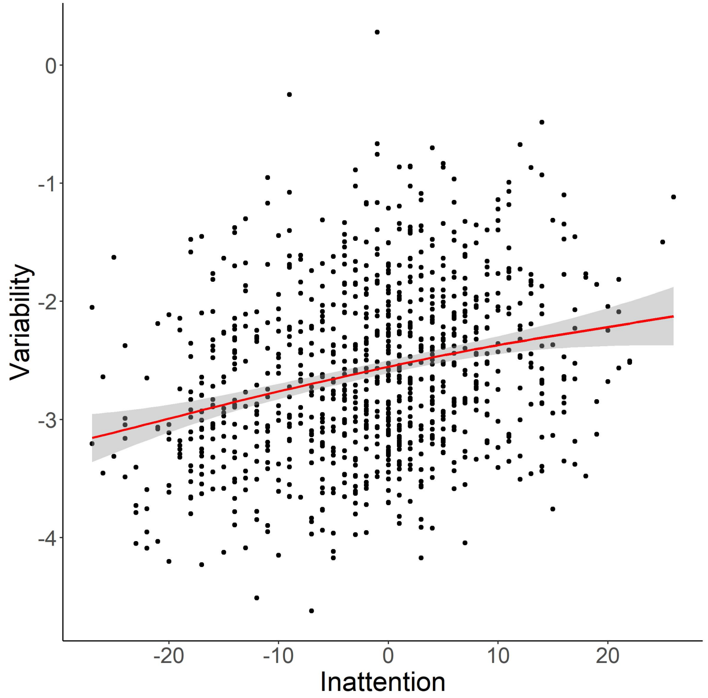
Local causes

- Differential strategies
- Task expertise

(in)Attention

- Increased frequency of lapses
- RT variability is a marker for ADHD
  - Hyperactivity
  - Inattention

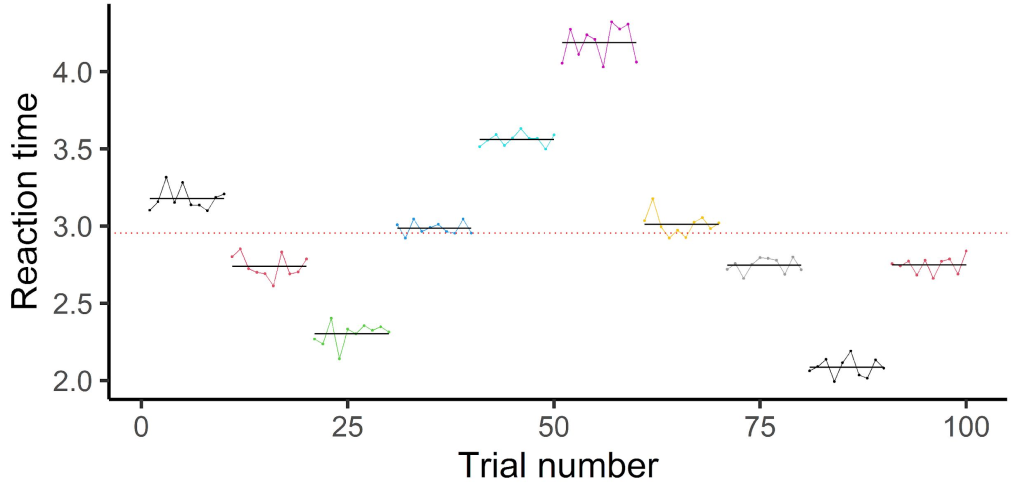
- Variability was found to be predictive of inattention symptoms yet *not* hyperactivity (n = 1121 children)
- Attentiveness was found to modulate variability



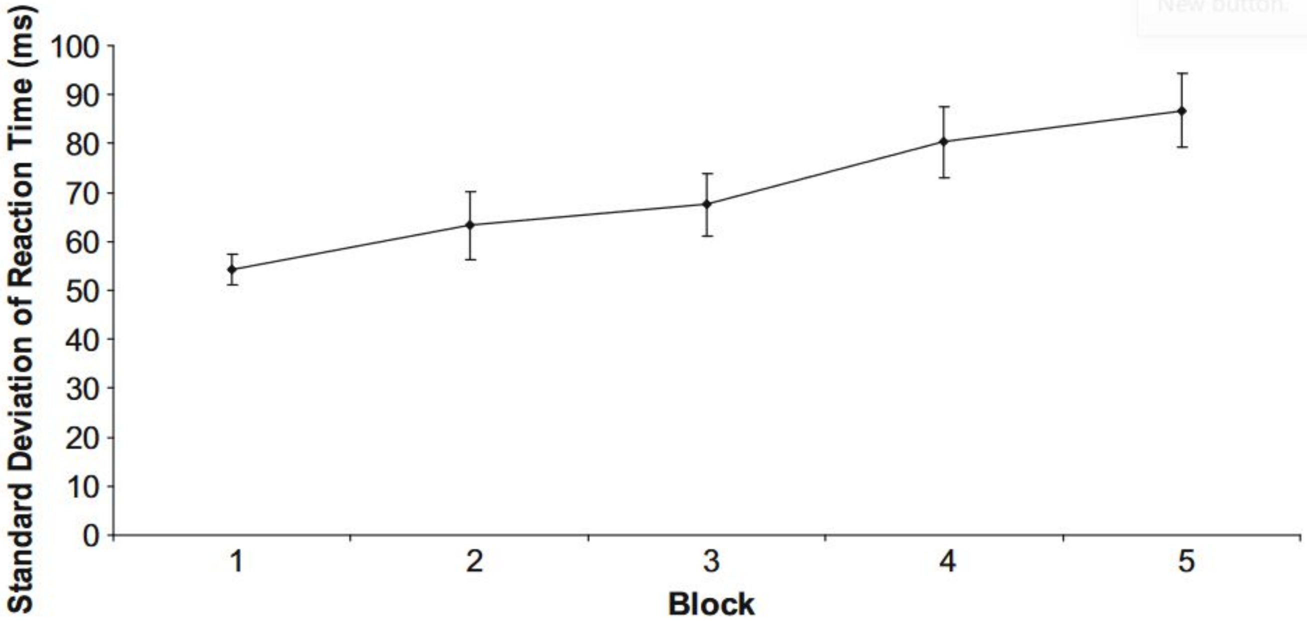
Kofler *et. al.*, 2013
Aristodemou *et. al.*, 2023

Fatigue

- We know sleep deprivation leads to worse cognitive functioning (Bruin et al., 2017)



- Fatigue has been linked to variability
  - Trial level
  - Day level



Unsworth & Robison, 2016
Galeano–Keiner et al., 2021
Könen, Dirk & Schmiedek, 2014

Sensory processing

- Variability in sensory processes could cause interindividual differences in encoding efficiency
- Endogenous neuronal noise (Li, von Oertzen & Lindenberger, 2006)

Neuron

Perspective

Behavior needs neural variability

Leonhard Waschke,[1,2,6,*] Niels A. Kloosterman,[1,2] Jonas Obleser,[3,4,5] and Douglas D. Garrett[1,2,5]

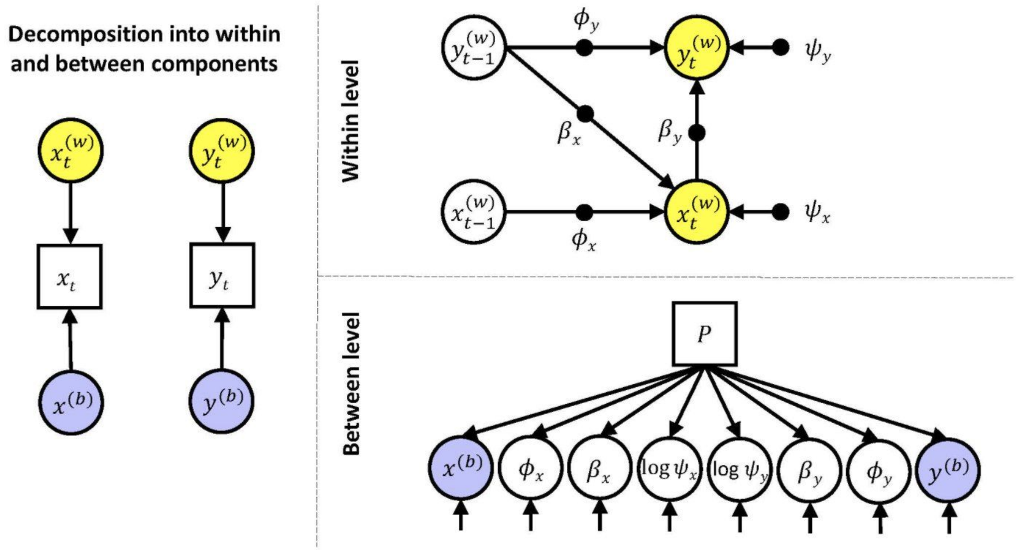
DSEM overview

Dynamic Structural Equation Modelling

- Overcomes many previous limitations
  - Conflation of parameters, convergence challenges
- Combines
  - Time-series analysis (t >10/20)
  - Multilevel modeling (trials nested in days nested in people)
  - Structural equation modeling
    - Variables can be cause/consequence
    - Include latent variables

Multilevel Model 3

In the third multilevel model, we include an observed predictor for the random effects at the between level.



Asparouhov, T., Hamaker, E. L., & Muthén, B. (2018). Dynamic structural equation models. *Structural Equation Modeling: A Multidisciplinary Journal*, *25*(3), 359-388.

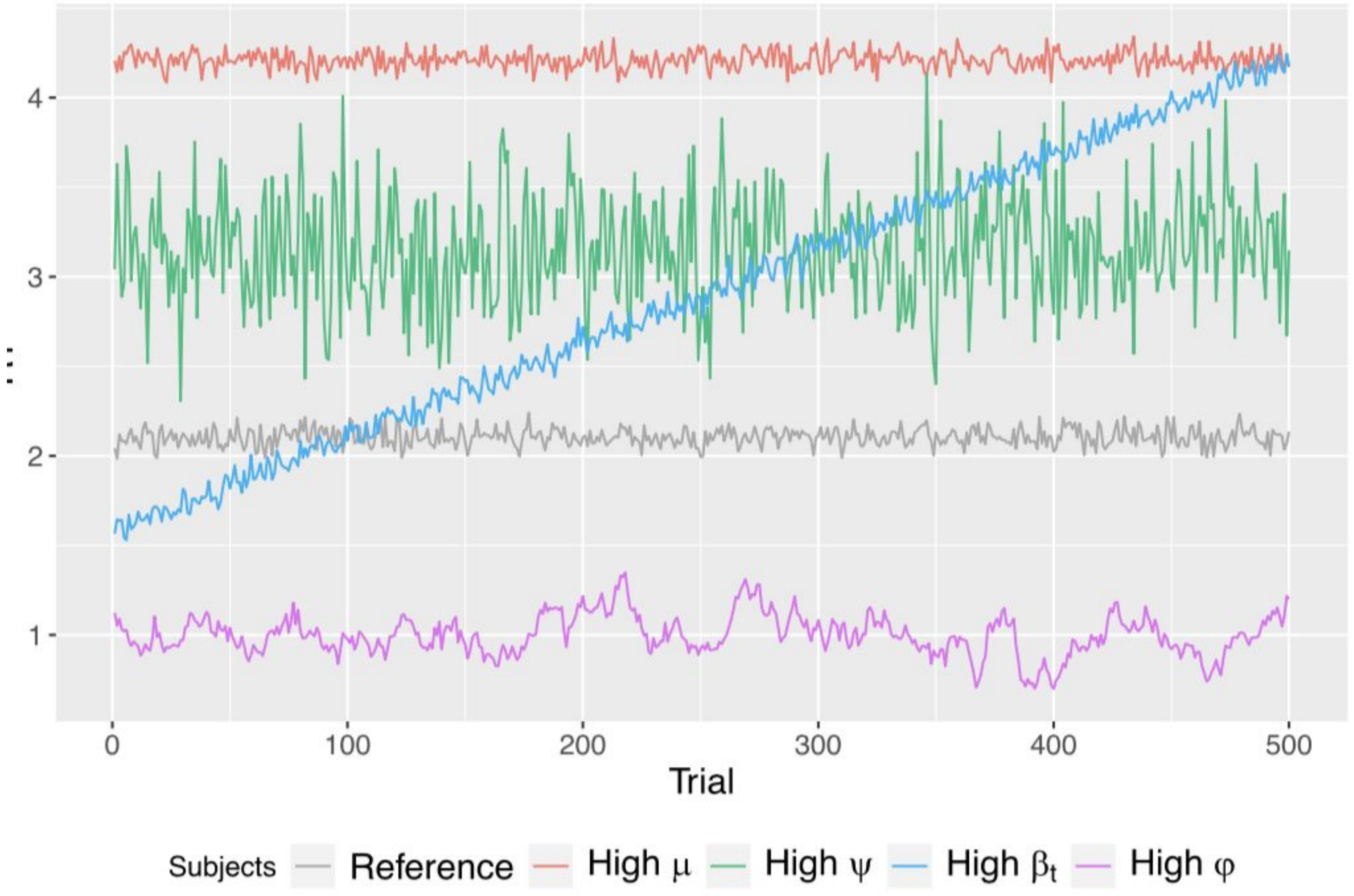
Hamaker, E. L., Asparouhov, T., Brose, A., Schmiedek, F., & Muthén, B. (2018). At the

DSEM in action: Level 1

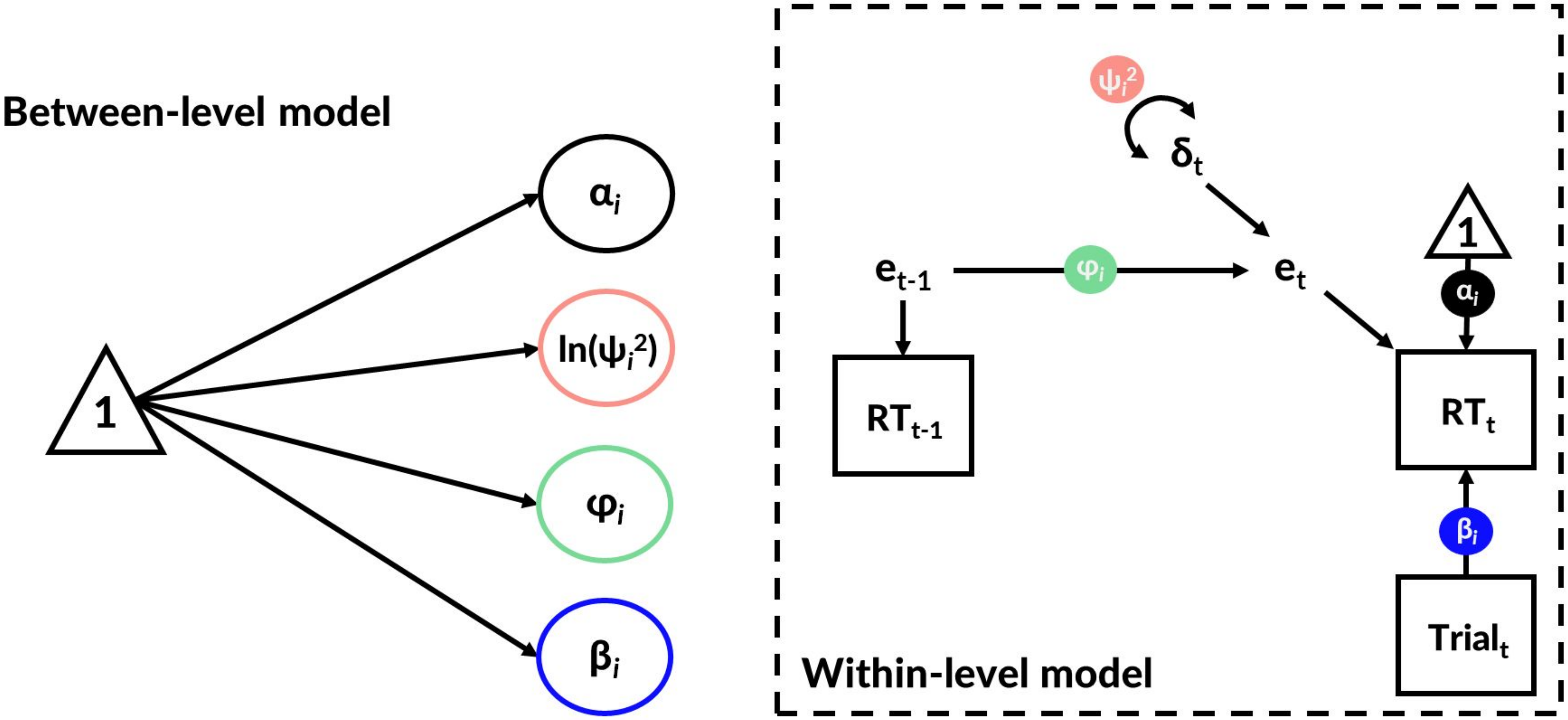
$$\log(RT_{t,i}) = \mu_i + \varphi_i RT_{t-1,i} + \beta_{ti} Trial_{t,i} + \varepsilon_{t,i}$$

$$\varepsilon_{t,i} \sim N(0, \psi_i)$$

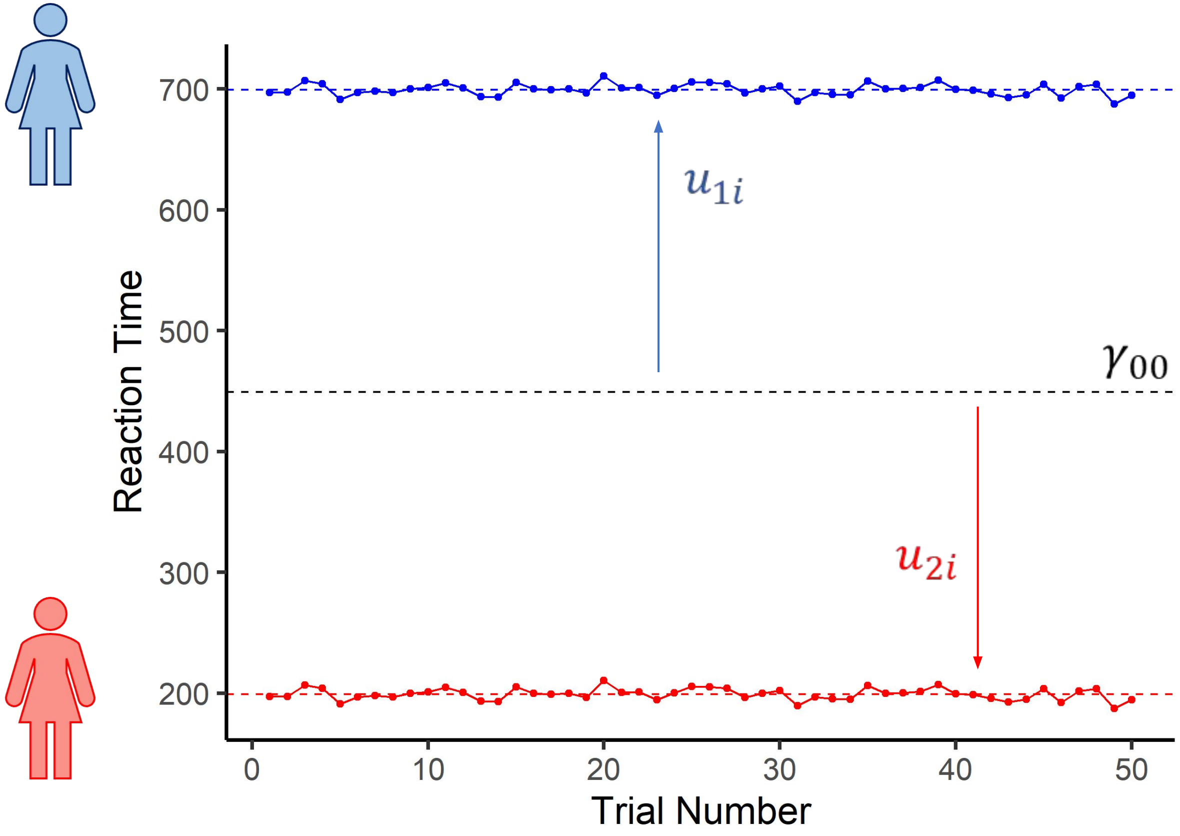
- (log) reaction time at time t for person i
- A function of
  - Mean (μ_i)
  - Trend (β) (training, growth)
  - Autoregression (φ) (mean reversion)
  - Residual variability (ε_{ti})

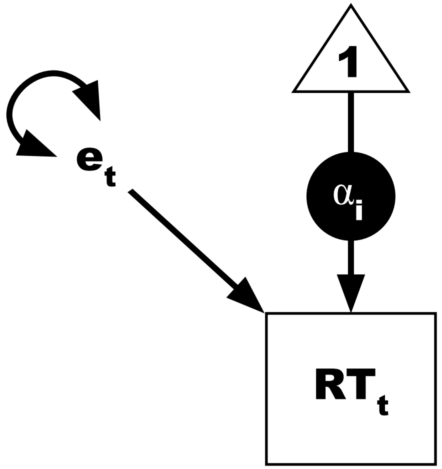


Isolate cognitive fluctuations via DSEM

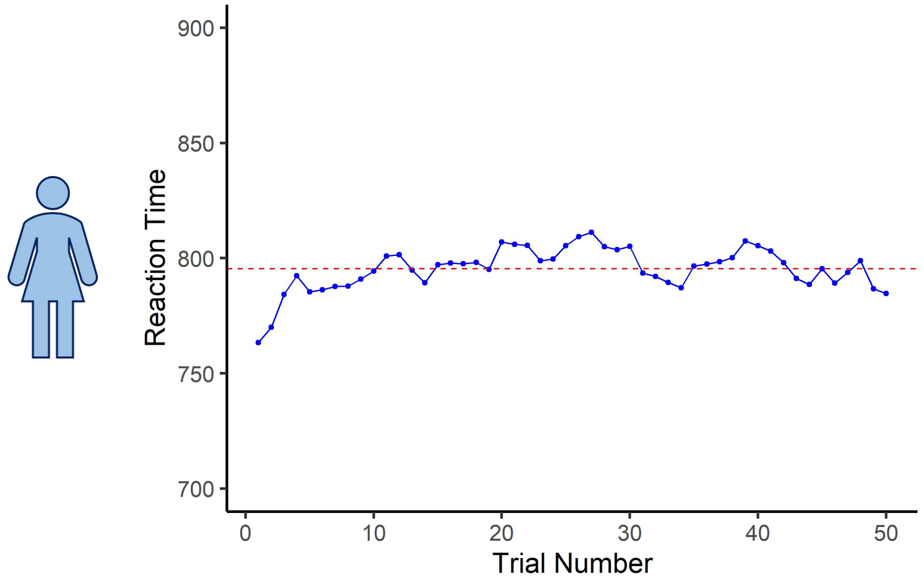


MEAN RESPONSE SPEED

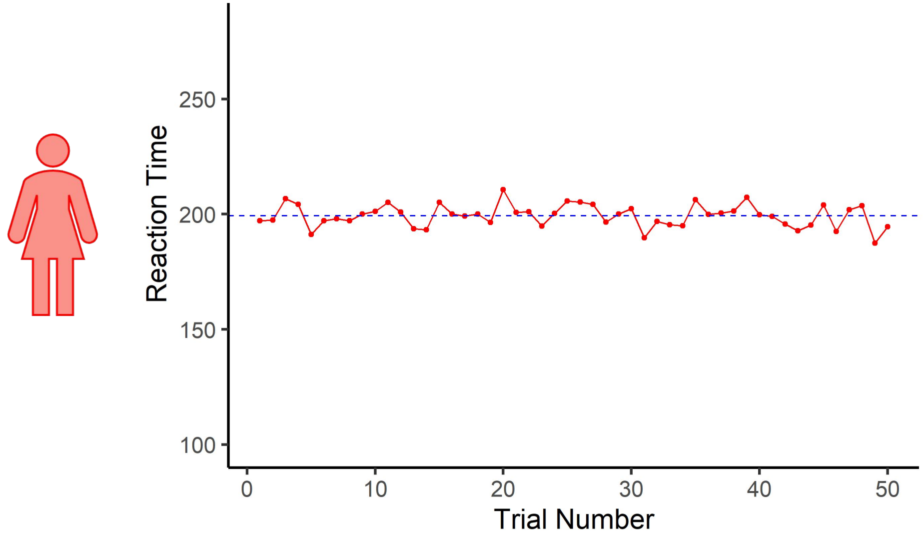




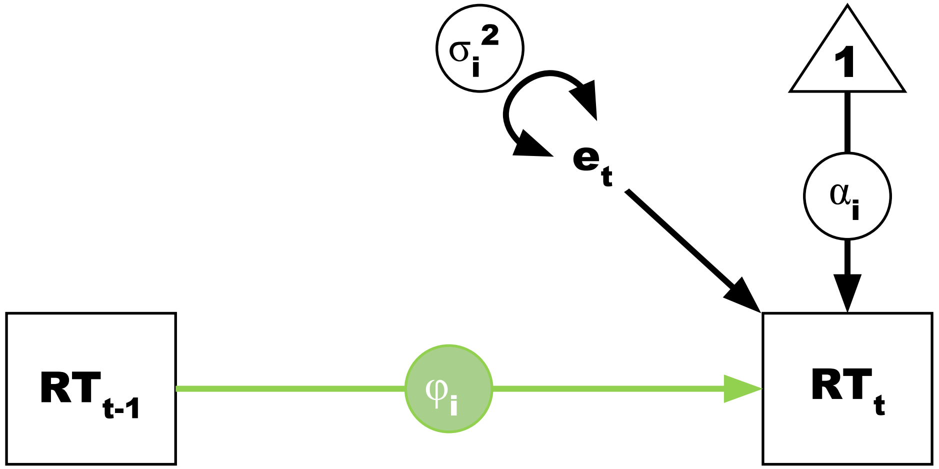
INERTIA (SPILLOVER)



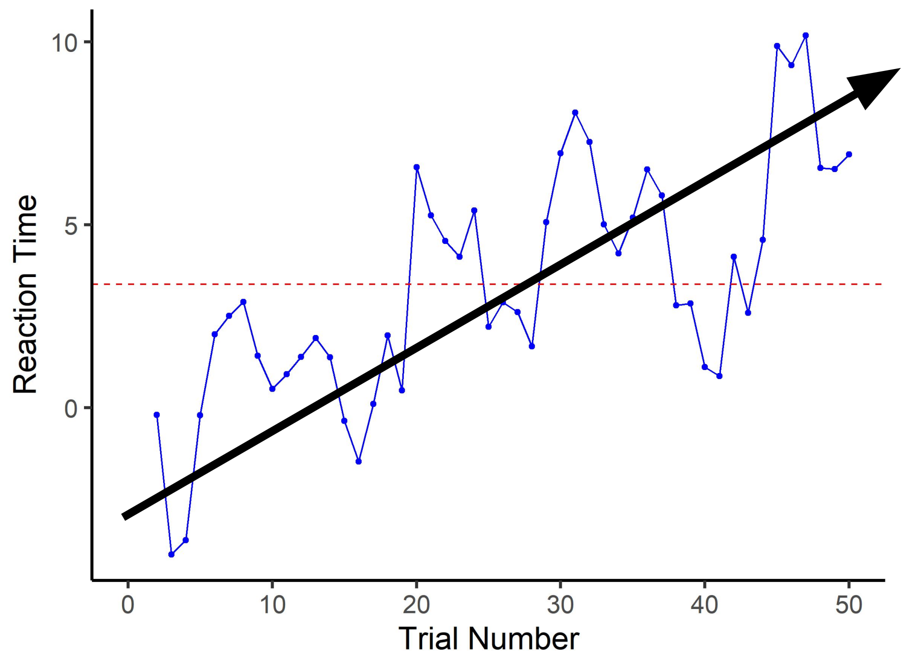
High AR(1)

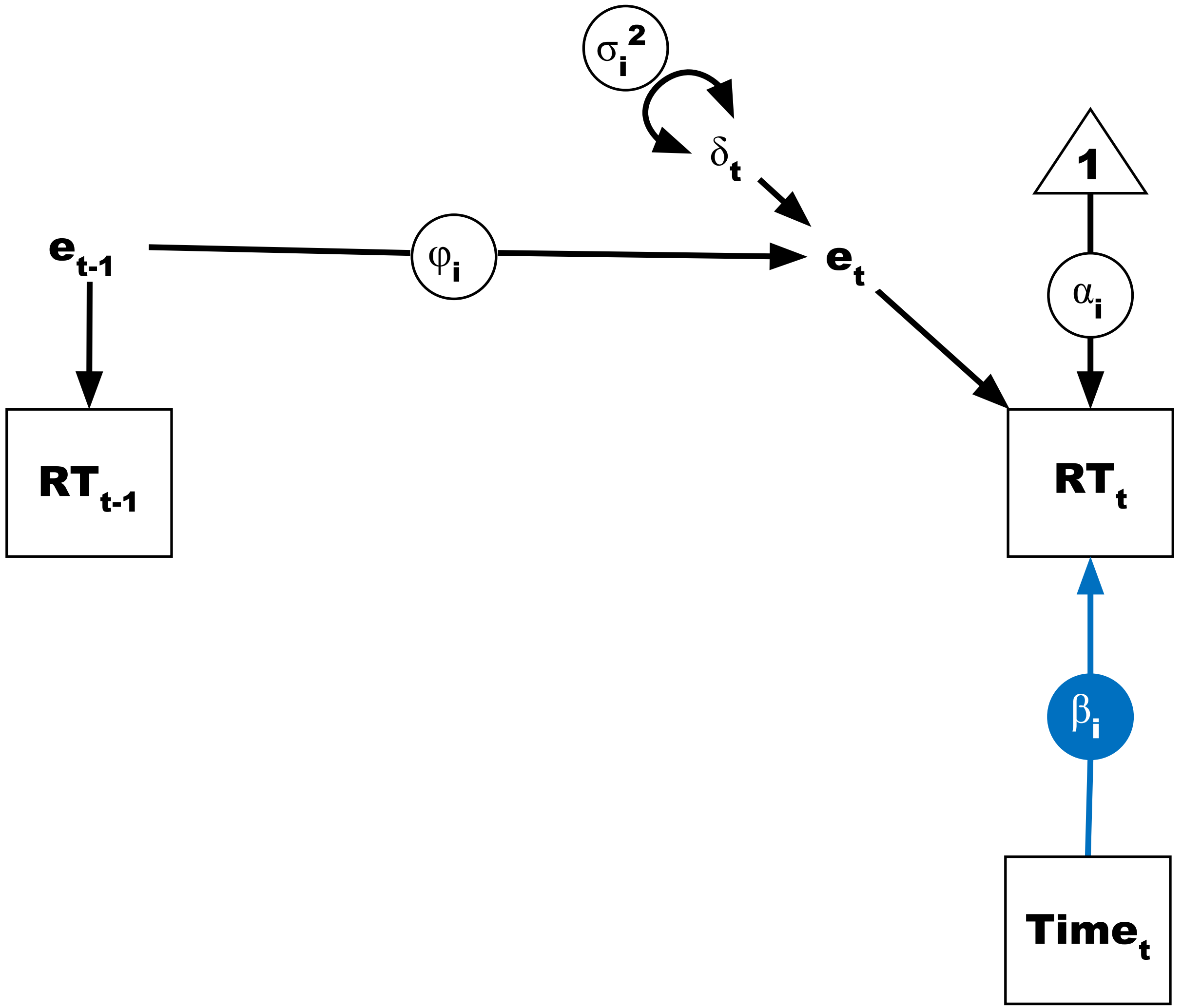


Low AR(1)

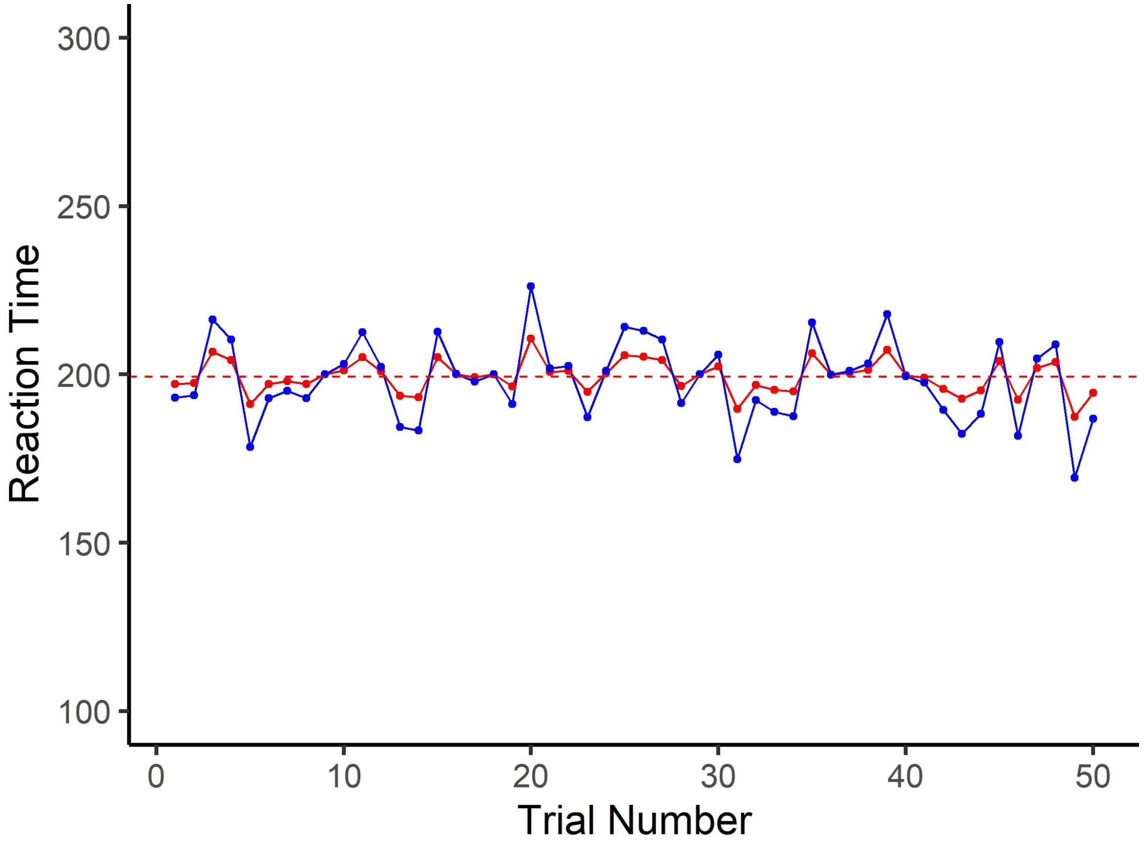


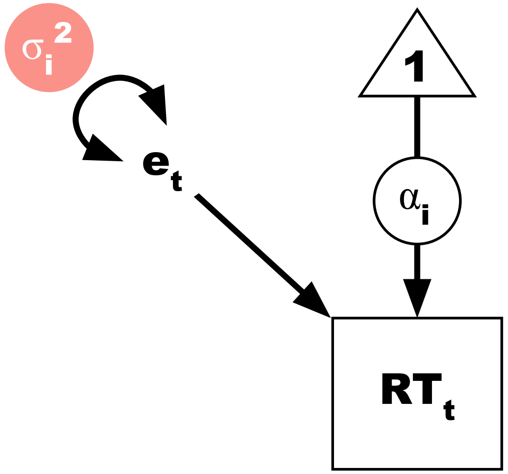
SYSTEMATIC CHANGE





TRIAL-TO-TRIAL VARIABILITY

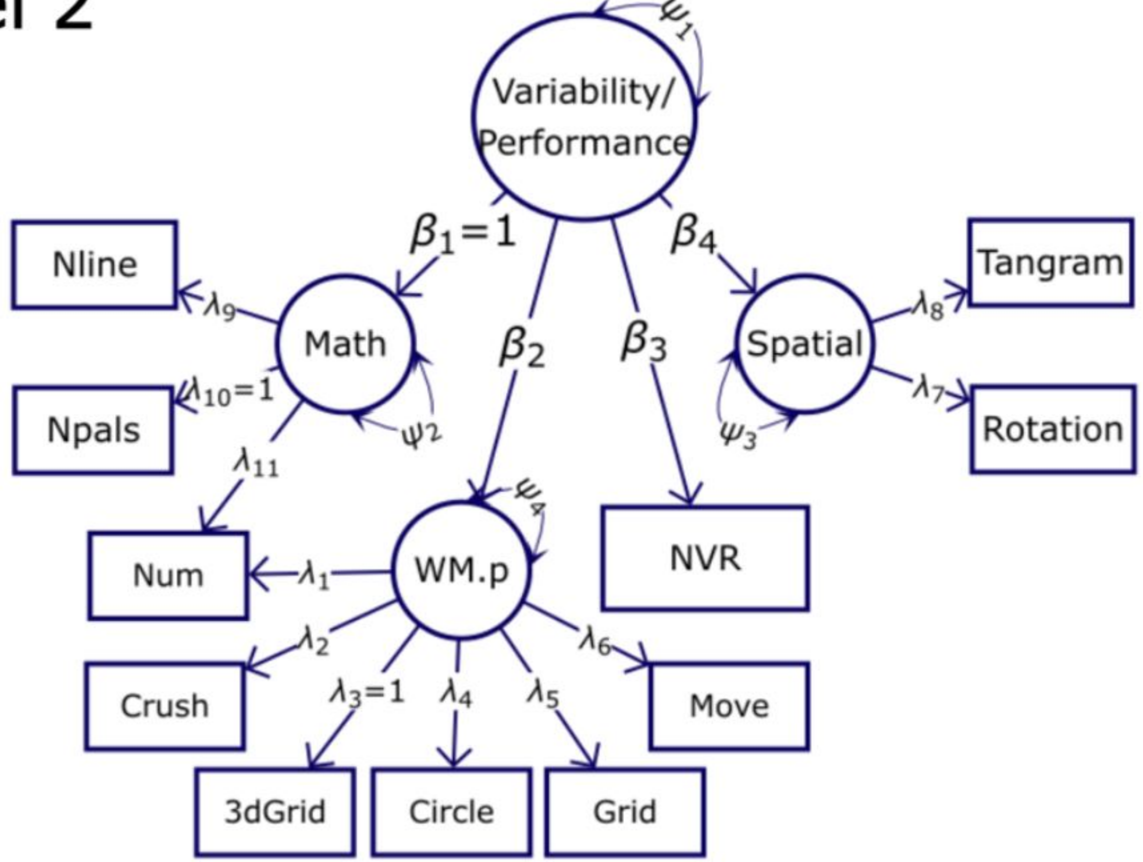




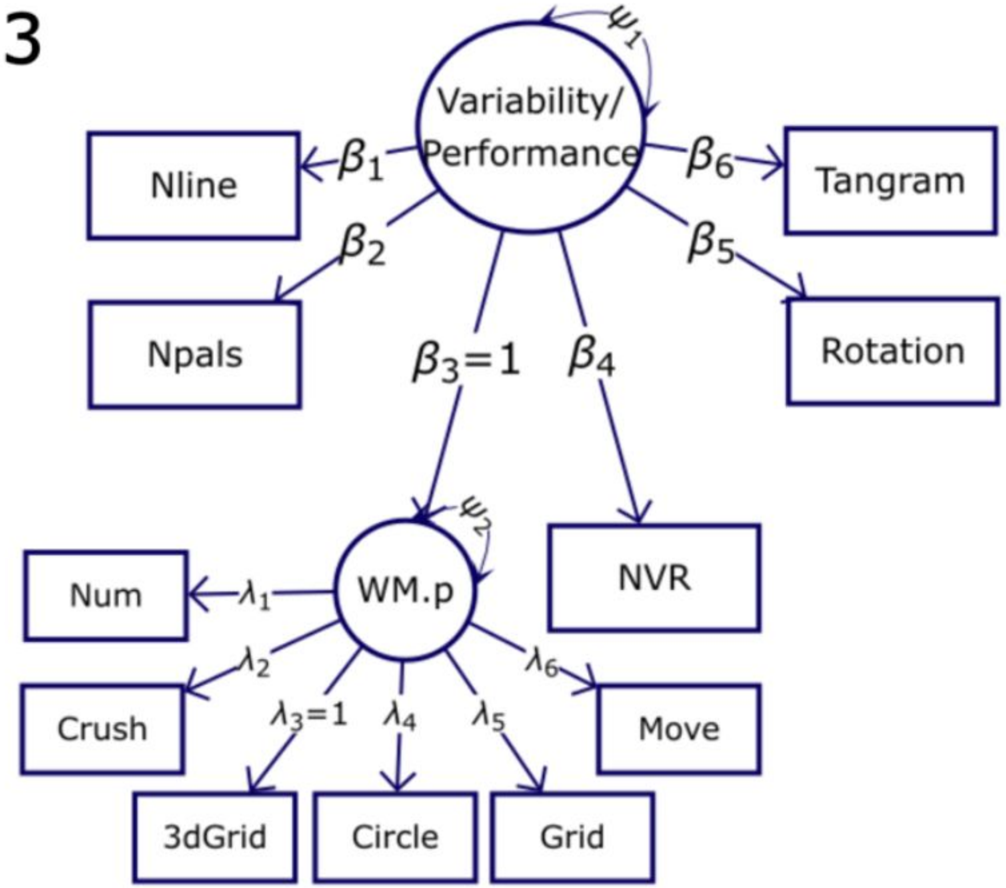
CFA results

CFA slide

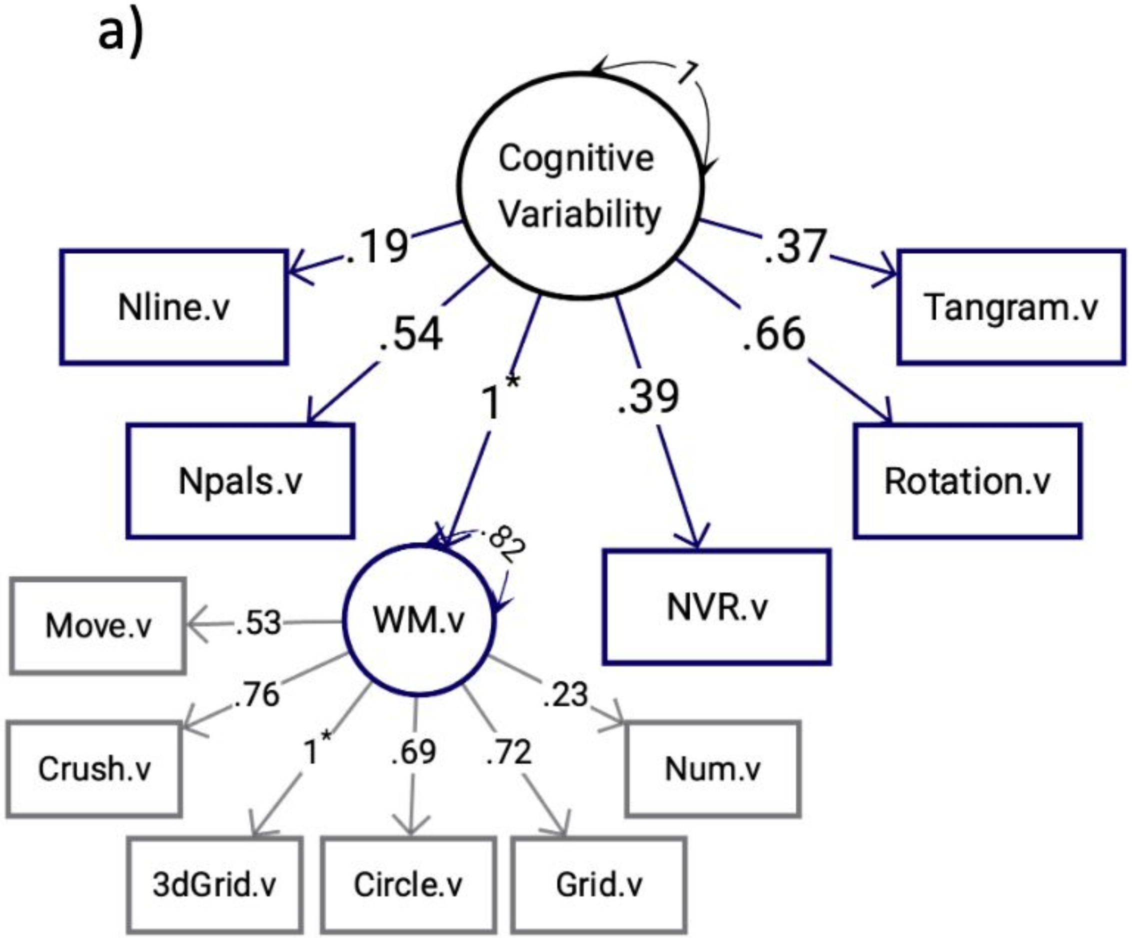
b) Model 2

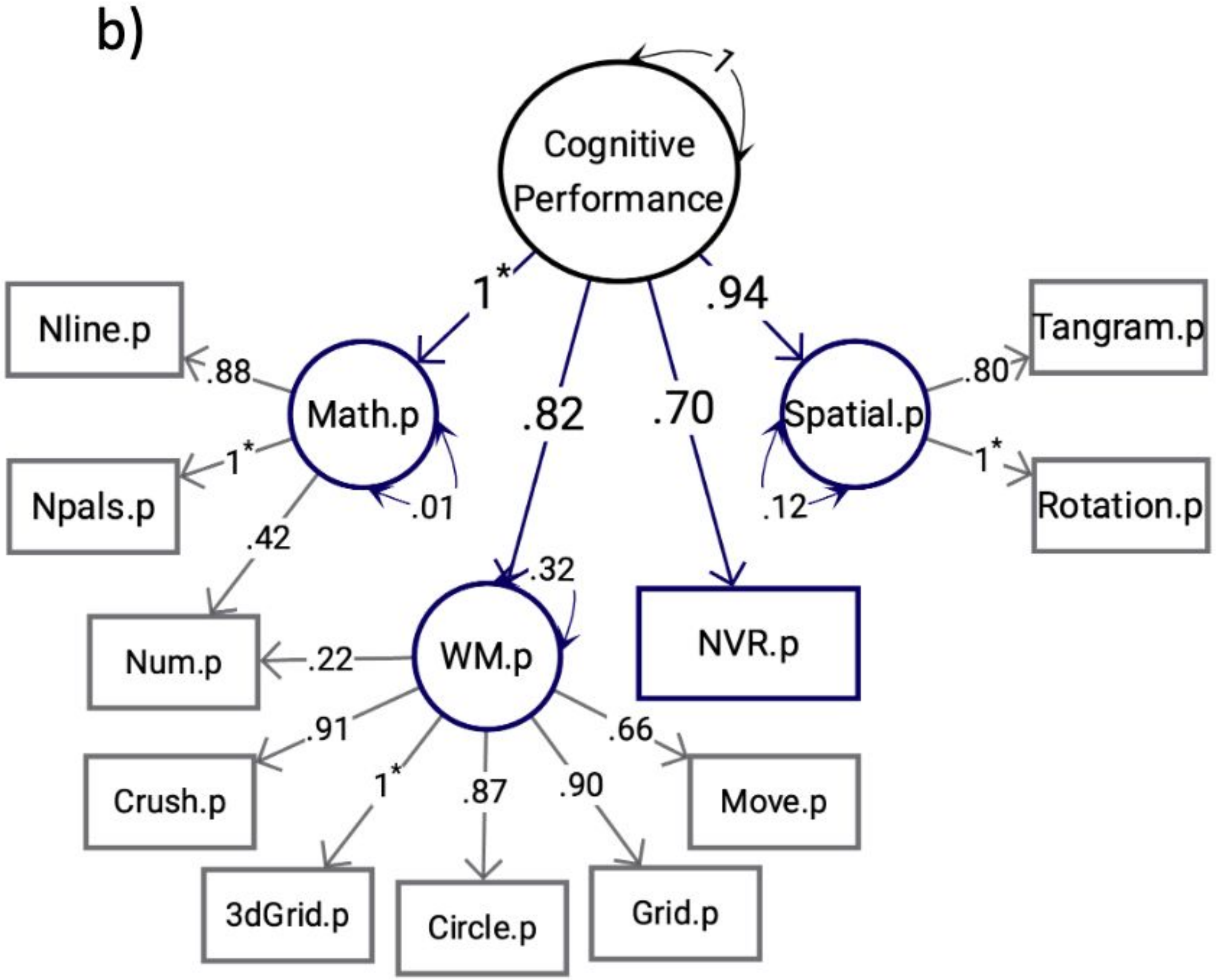


c) Model 3



CFA slide


a)
Cognitive Variability
1
.19
.37
Nline.v
Tangram.v
.54
.66
1*
.39
Npals.v
Rotation.v
.82
NVR.v
Move.v
.53
WM.v
.76
.23
Crush.v
1*
.69
.72
Num.v
3dGrid.v
Circle.v
Grid.v


b)
Cognitive Performance
1
1*
.94
Nline.p
Tangram.p
.88
Math.p
.82
.70
Spatial.p
.80
1*
1*
Npals.p
.01
.12
Rotation.p
.42
.32
Num.p
.22
WM.p
NVR.p
.91
.66
Crush.p
1*
.87
.90
Move.p
3dGrid.p
Circle.p
Grid.p

Day to day fluctuations

Day to Day fluctuations

- For WM grid there is no day to day fluctuations, yet this changes for other tasks (i.e., NVR)

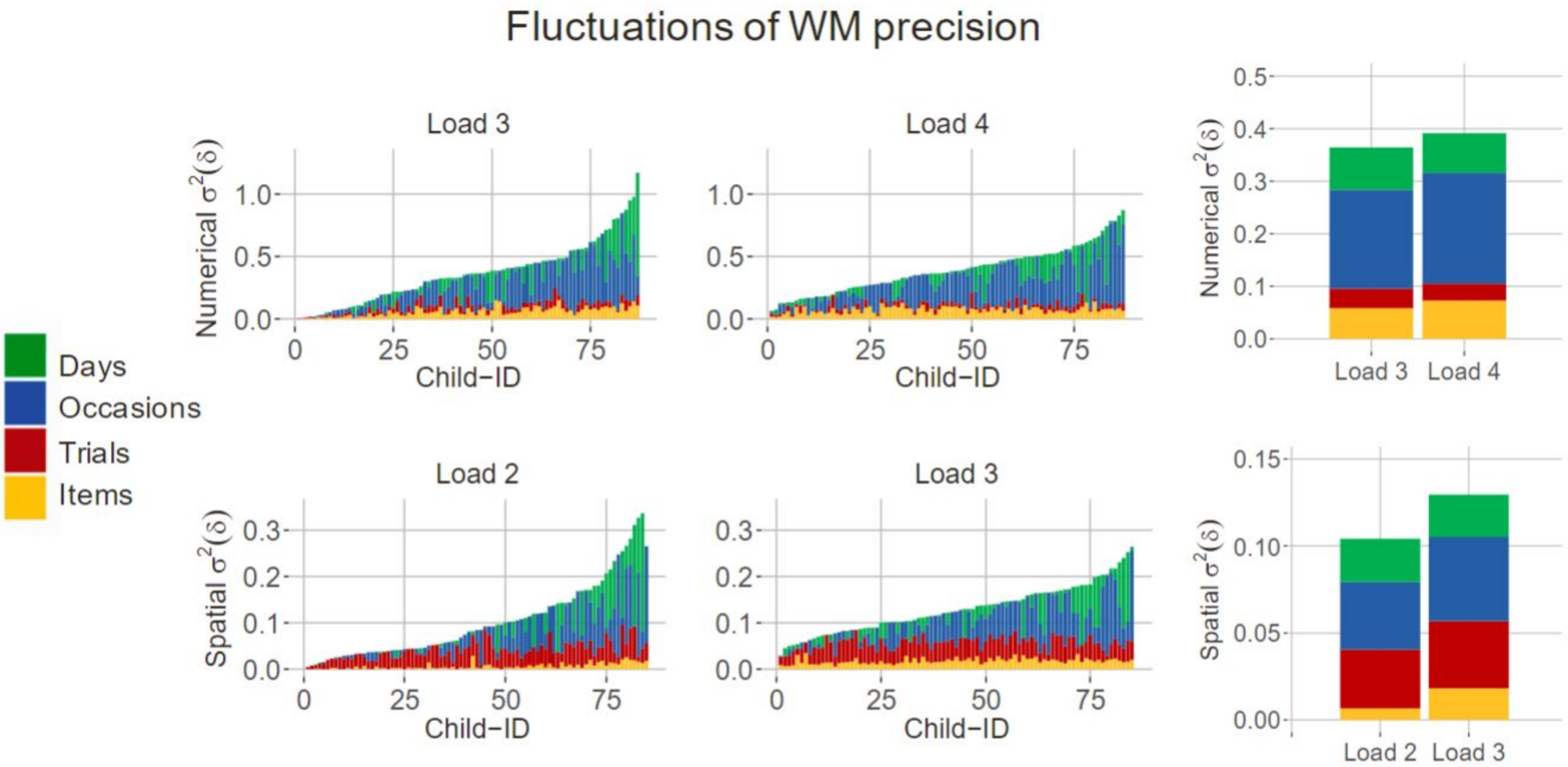
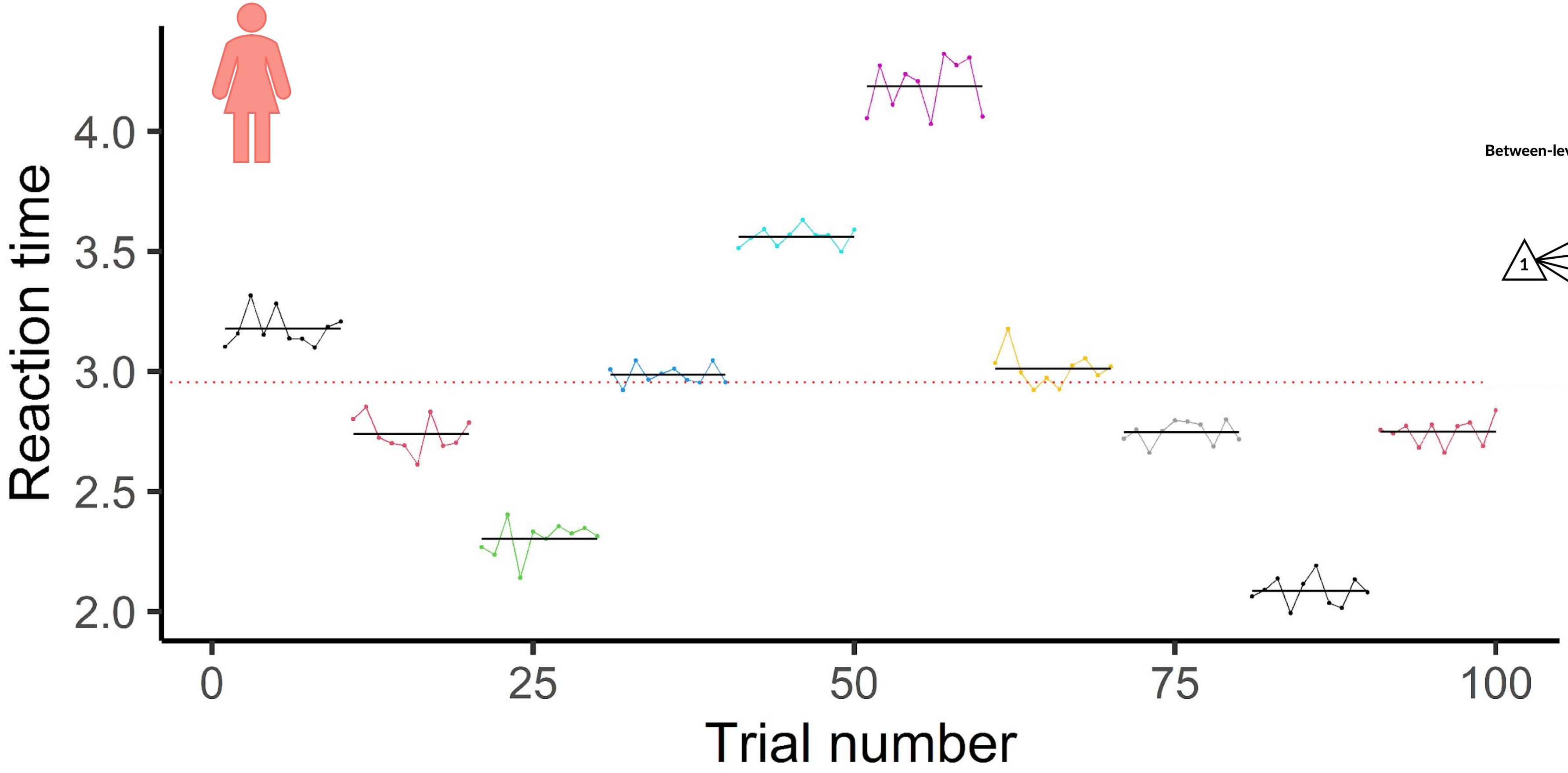
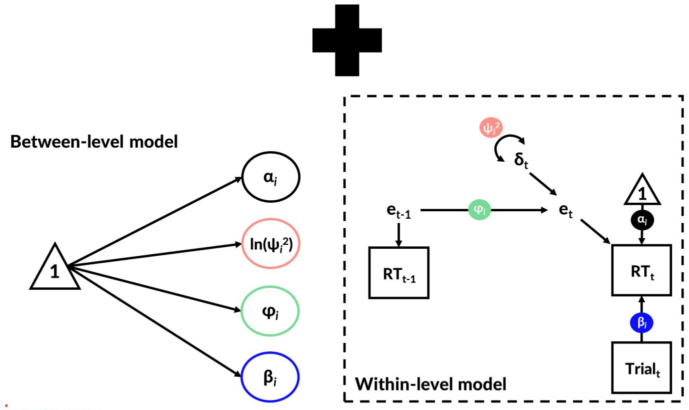


Figure from *Galaeno-Keiner et al., 2022*

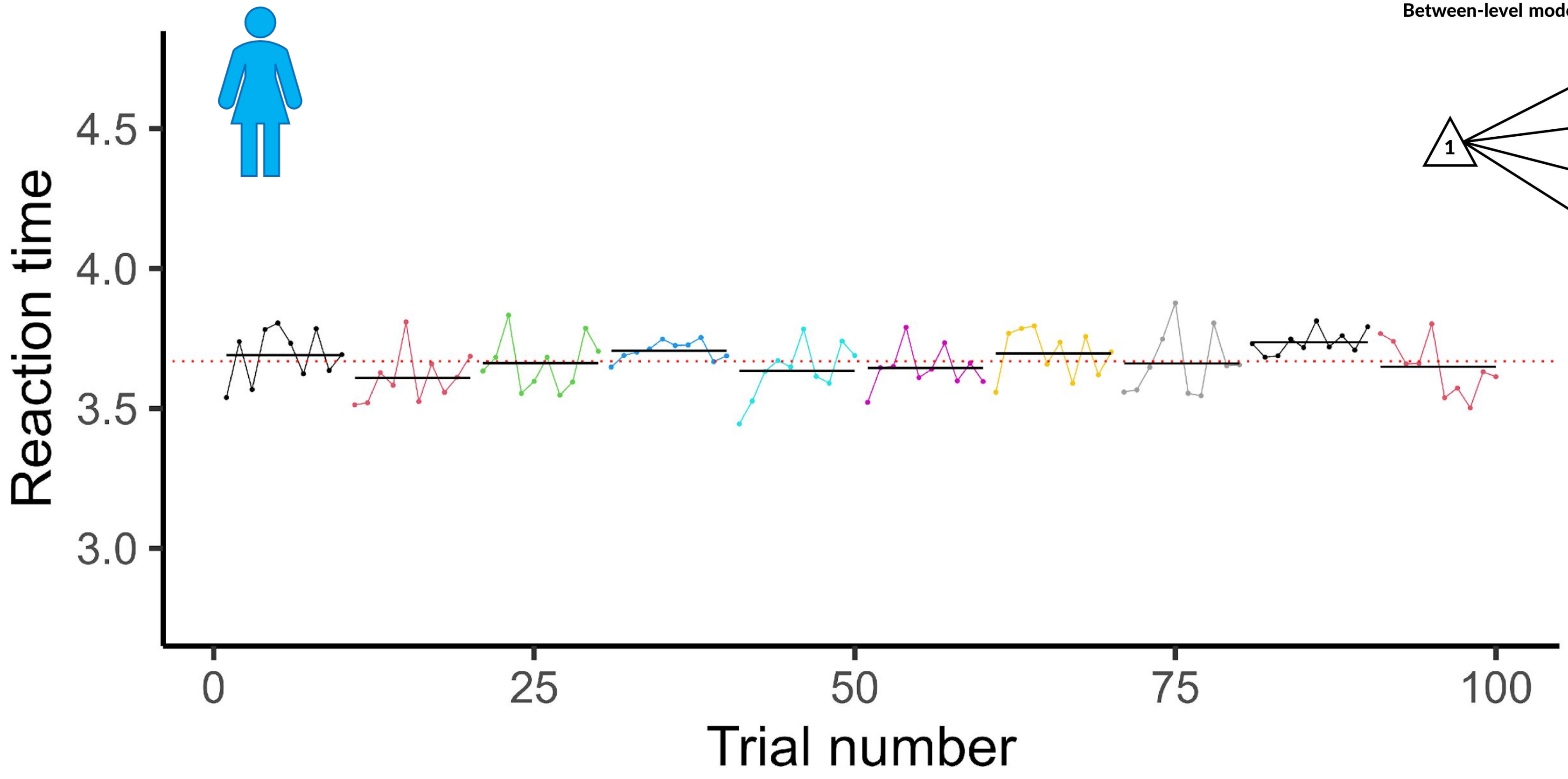
If we *fluctuate* from day to day…

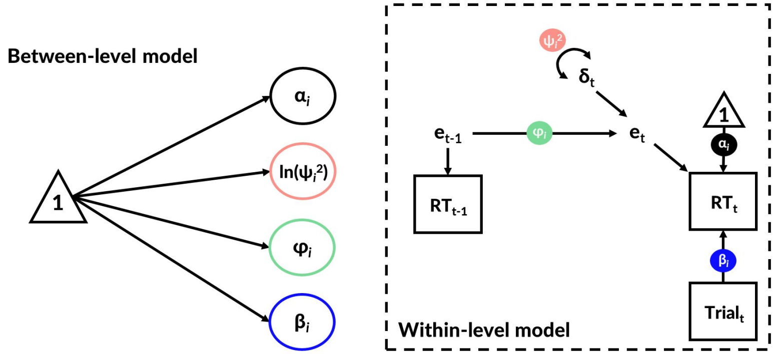


Day-to-day variance



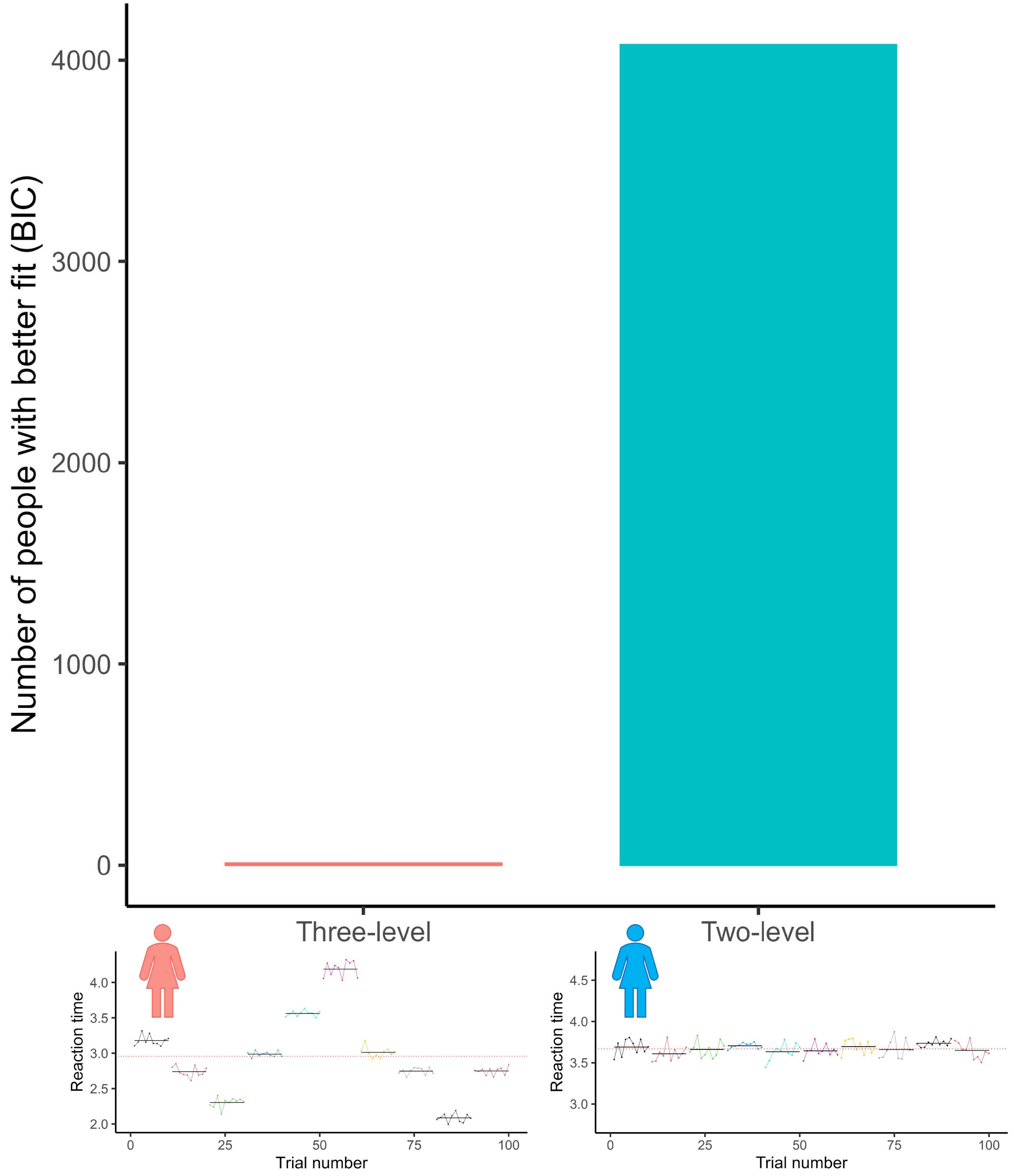
If we are *consistent* from day to day…

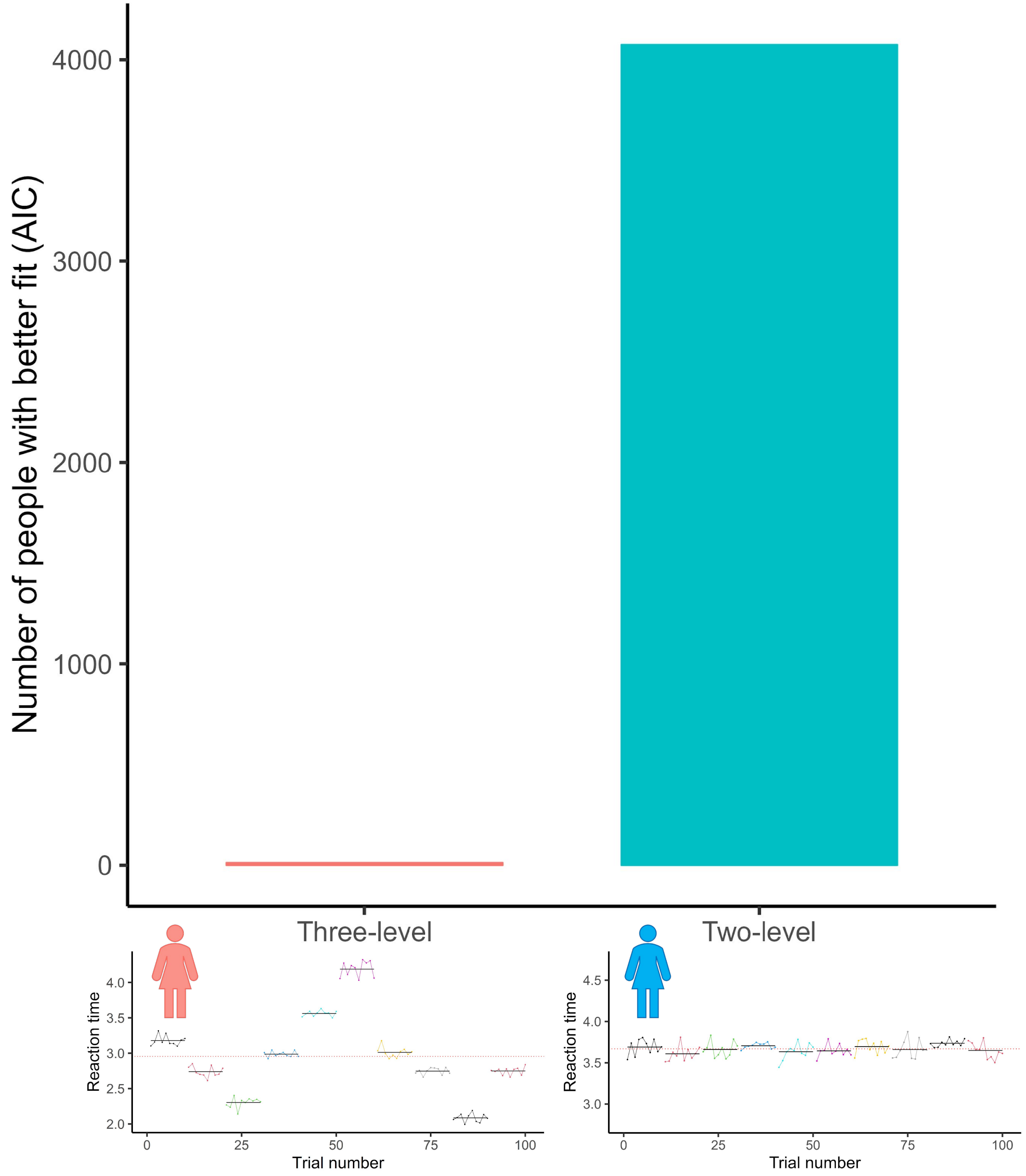




For 4090 people are CONSISTENT from day-to-day

RT





For 4051 people are CONSISTENT from day-to-day

SPAN