FUNCTION AND NATURE OF SERIAL ORDER IN WORKING MEMORY

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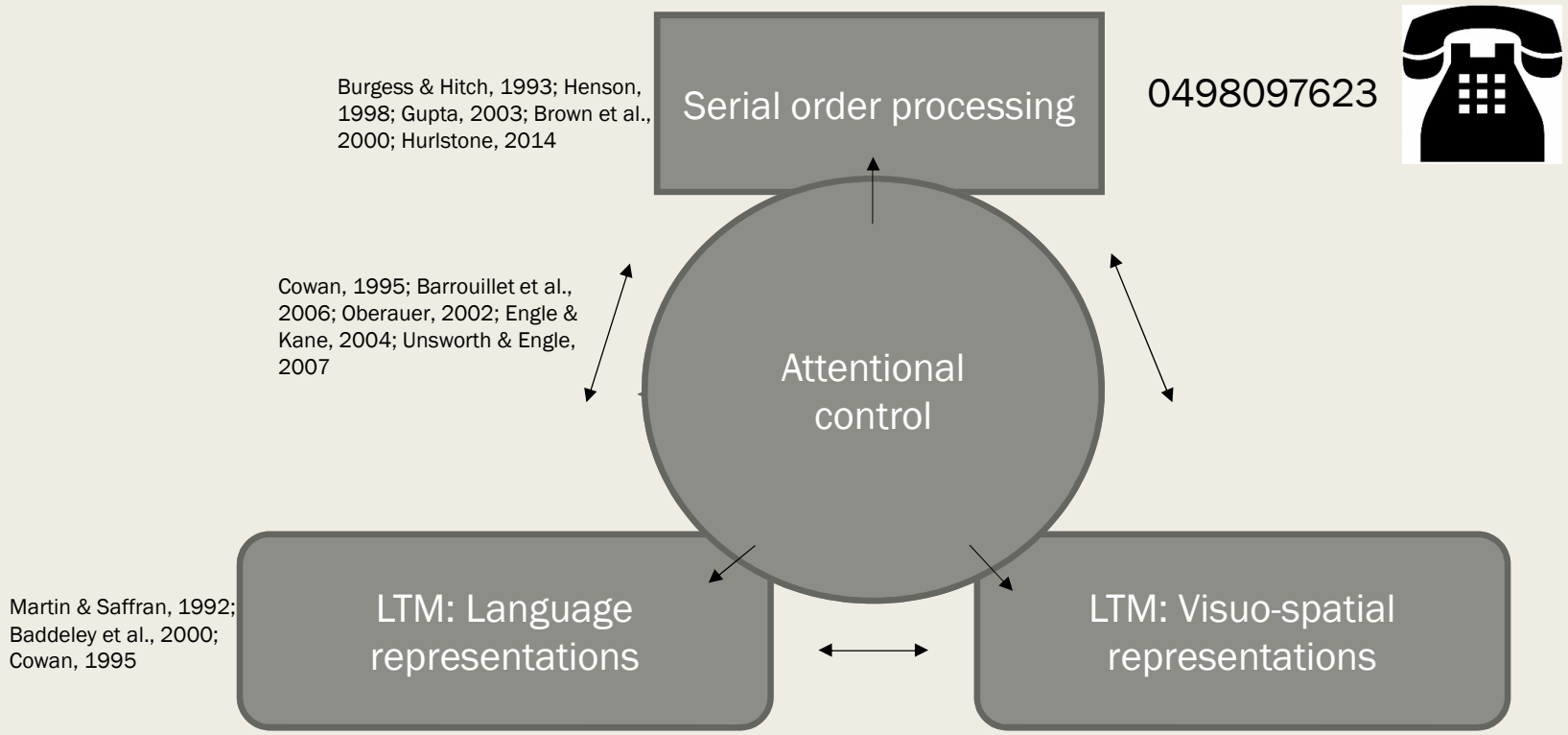
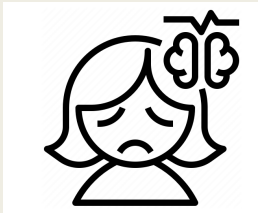
Theoretical framework

Working memory = capacity to temporarily maintain information in mind and to mentally manipulate it during a short period when we want to reach a specific goal (Cowan & Alloway, 2009).

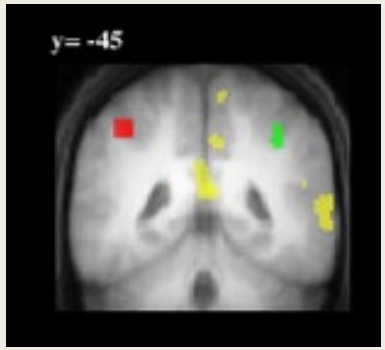


Specific component

- Serial order is a specific and independent component
  - *Distinct impairment in brain-damaged patients or atypical developmental disorders* *(Attout et al., 2012; Majerus et al., 2017; Majerus et al., 2018)*



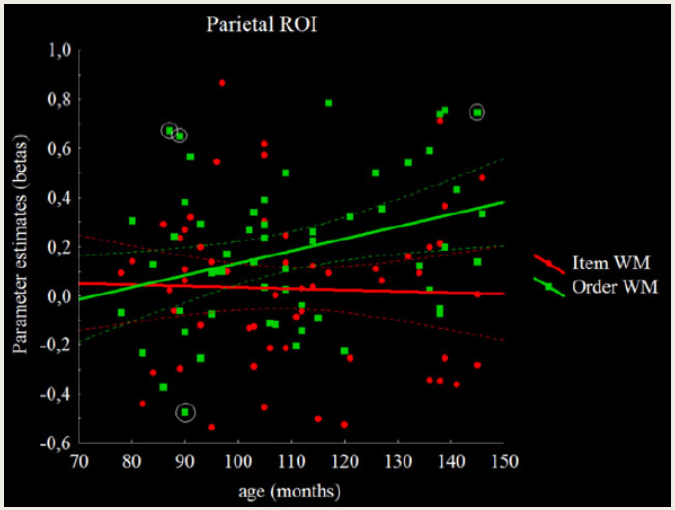
  - *Distinct cerebral networks in adults and children*



Majerus et al. (2006), NI

Item WM

Order WM

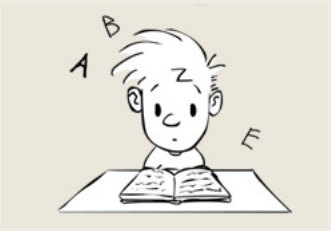


Attout et al. (2018), HBM

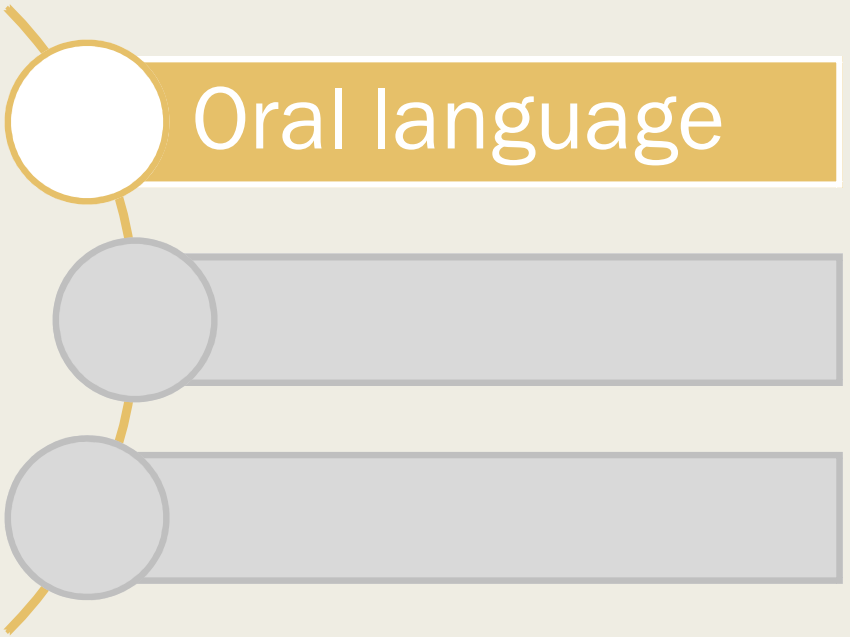
THE FUNCTION OF ORDER WM

Serial order WM

To create a long-term and sustainable representation of the information

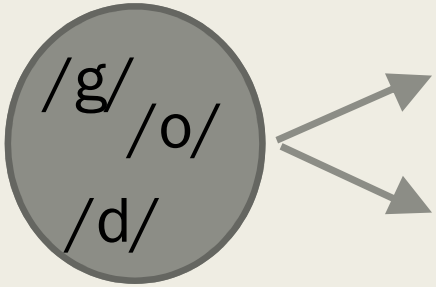


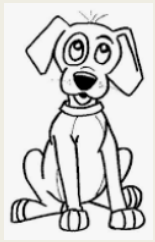
Serial order WM



Serial order WM & oral language

Language = letters → words





/dog/

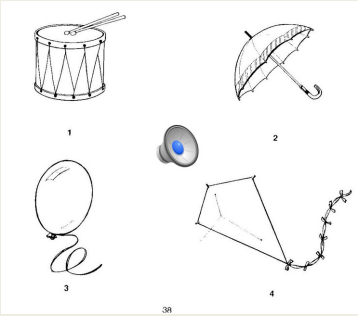
/god/

→ Importance of serial order processes in lexical knowledge and learning of new words

(Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe et al., 2006;
Majerus et al., 2008; Ordonez Magro, Attout, Majerus, & Szmalec, 2018)

Serial order WM & oral language

Receptive vocabulary



Productive vocabulary

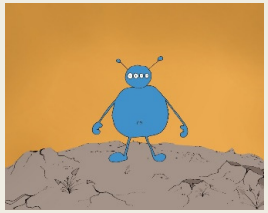
Table 2
Bayesian correlation (Pearson r) between the WM tasks and the different vocabulary measures and Raven's CPM.

	Item WM	Order WM
Receptive vocabulary	.09 (BF_{10} = 0.18)	.34 (BF_{10} = 28.12)
Productive vocabulary (total)	−.03 (BF_{10} = 0.14)	.33 (BF_{10} = 24.02)
Productive vocabulary (frequent words)	−.08 (BF_{10} = 0.18)	.29 (BF_{10} = 5.86)
Productive vocabulary (rare words)	−.01 (BF_{10} = 0.13)	.35 (BF_{10} = 45.45)
Productive vocabulary (verbs)	.04 (BF_{10} = 0.14)	.21 (BF_{10} = 0.93)
Raven's CPM	.19 (BF_{10} = 0.61)	.18 (BF_{10} = 0.53)

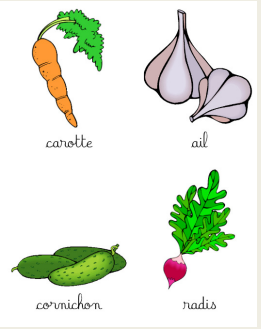
Attout, Grégoire, & Majerus (2020). Cognitive Development

Serial order WM & oral language

Order WM → Learning of new words



/bam/ ⟷



Ordonez Magro, Attout, Majerus, & Szmalec (2018). Cognitive Development

Serial order WM & oral language

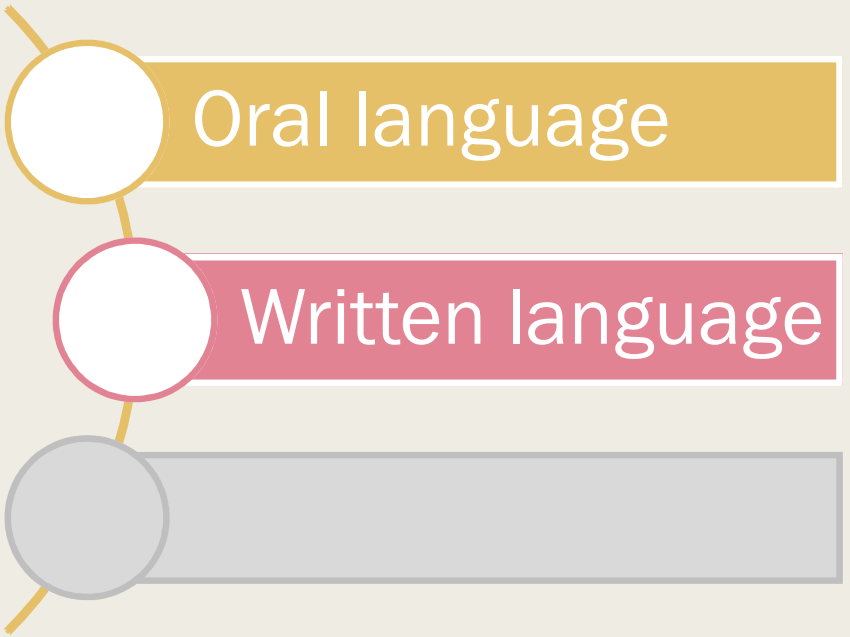
Syntactic skills

Order WM

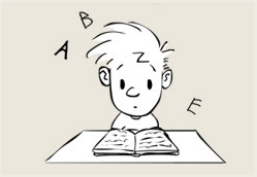
« A chicken that is hunting the fox »

Delage & Frauenfelder (2019)
Janvier, Attout & Delage, 2021 (Master thesis)

Serial order WM



Serial order WM & written language



Order WM

1st grade

First words reading
(G-P assembling)

mama

Reading words

thought

ISR task

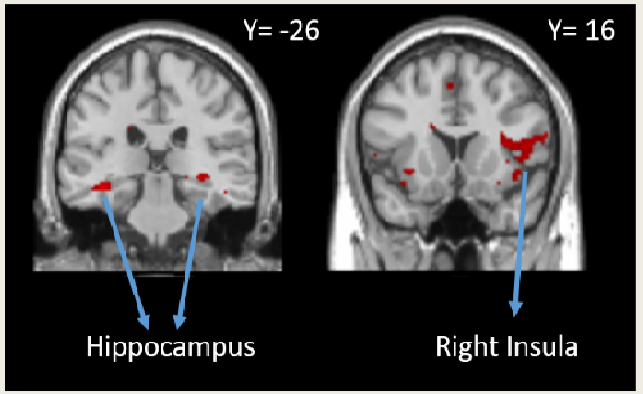
lou mo pi ra vu

ra pi vu mo lou

lou mo pi ra vu

pi mo ra lou vu

lou mo pi ra vu

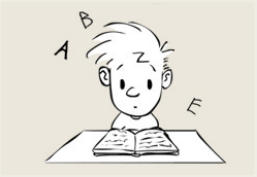


mama

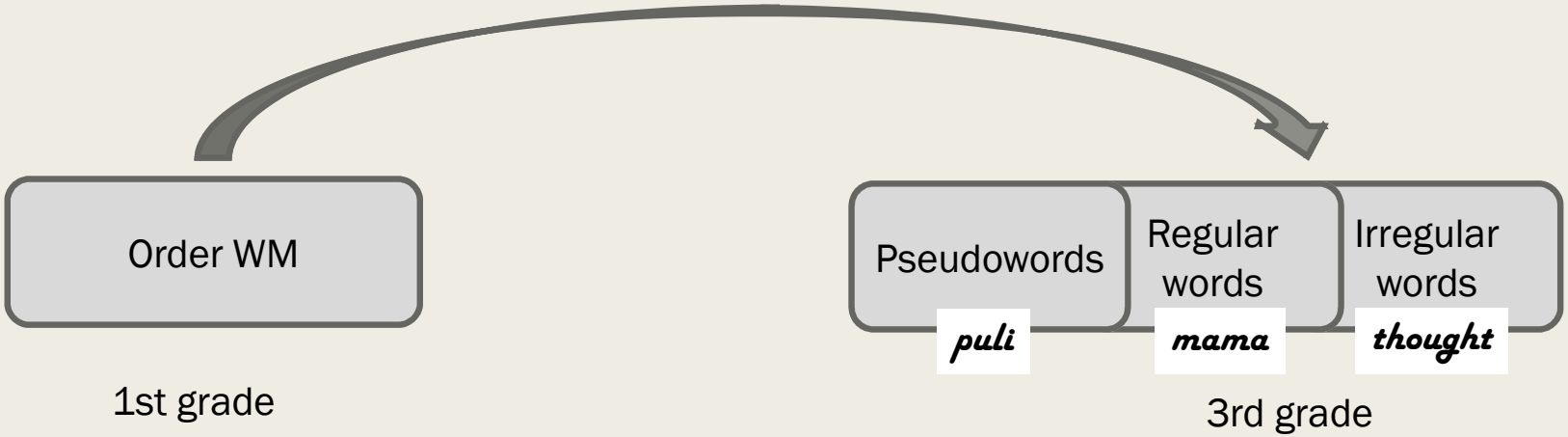
thought

Ordonez et al., 2020, Developmental psychology
Attout et al., 2020, HBM

Serial order WM & written language

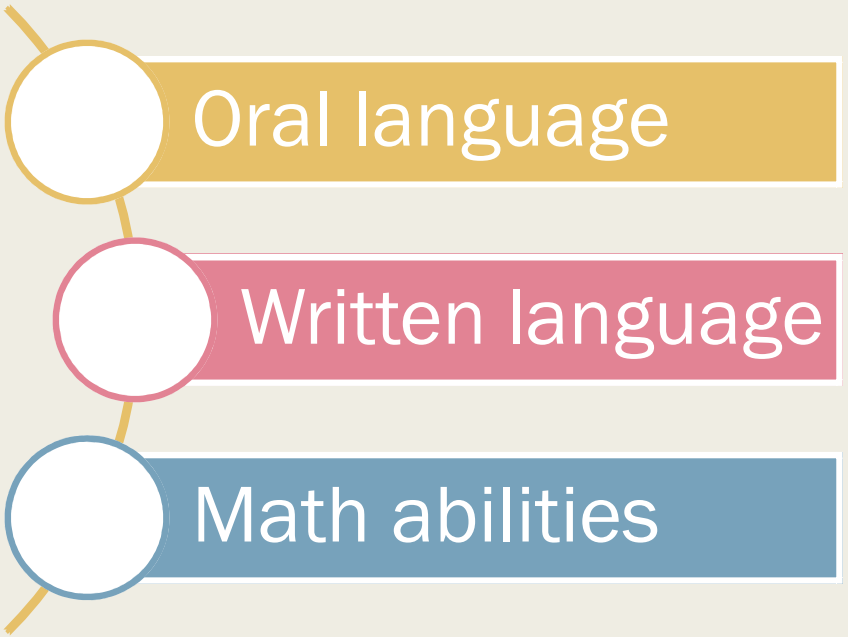


Spelling abilities

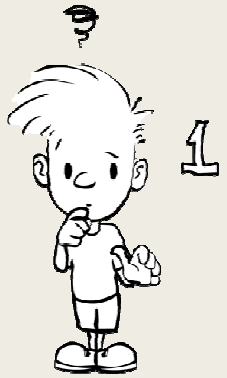


Ordonez et al., 2020, Cognition

Serial order WM



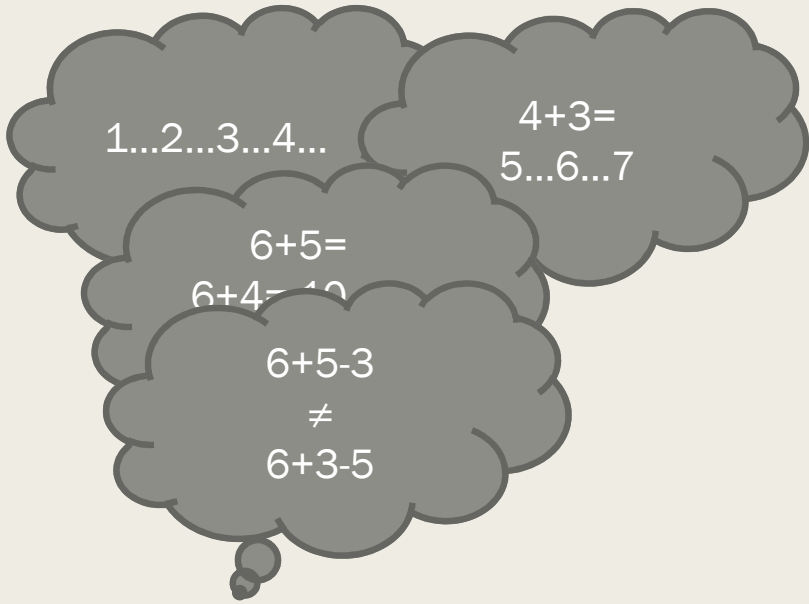
Serial order WM & maths



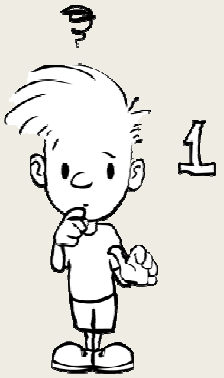
- *Verbal counting / first additions*

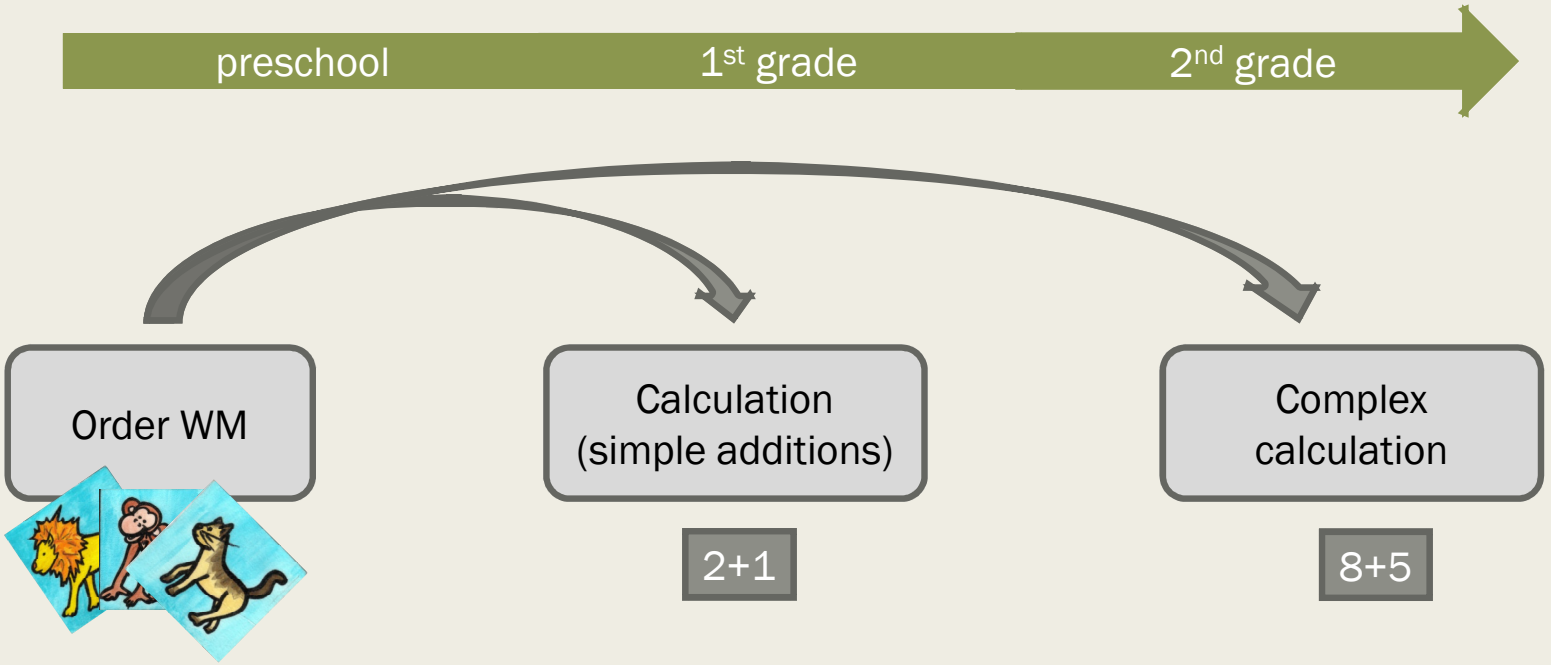
  To know which number has already been counted
- *To solve a more complex calculation*

  To recall an interim result
- *To maintain the order of events*



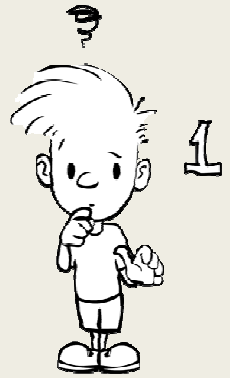
Serial order WM & maths



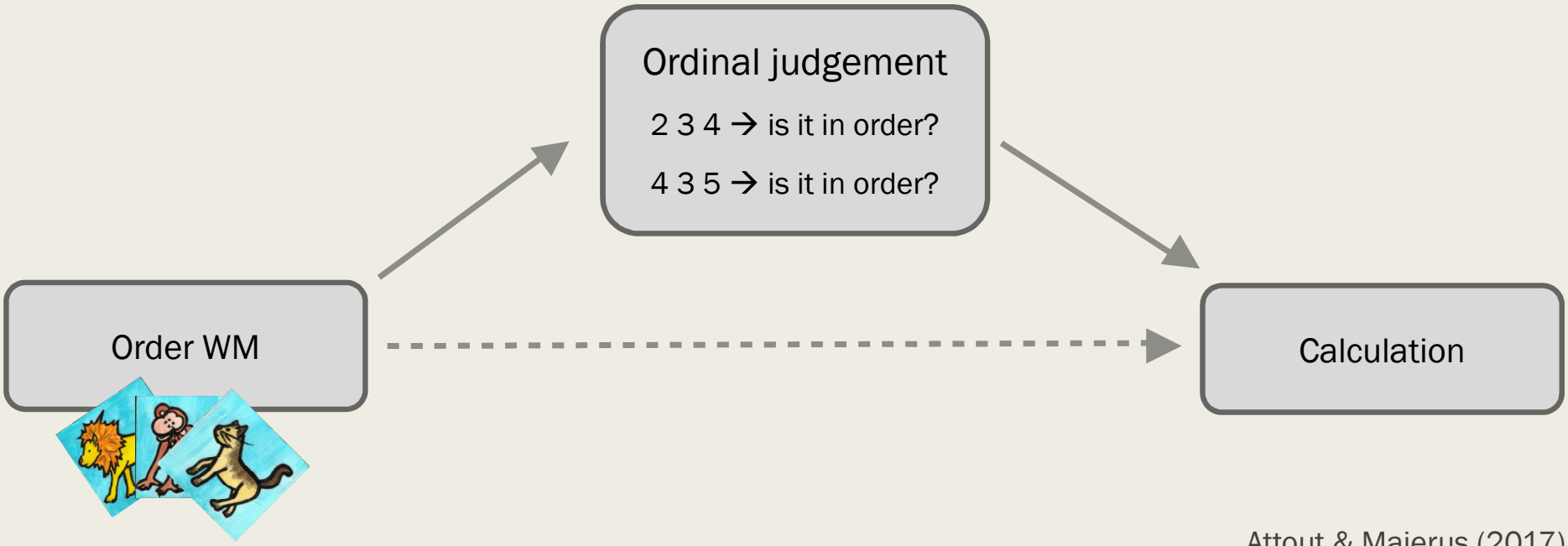


Attout, Noël, & Majerus (2014). *Developmental Psychology.*

Serial order WM & maths

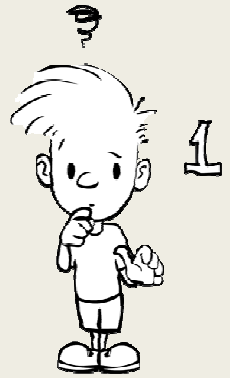


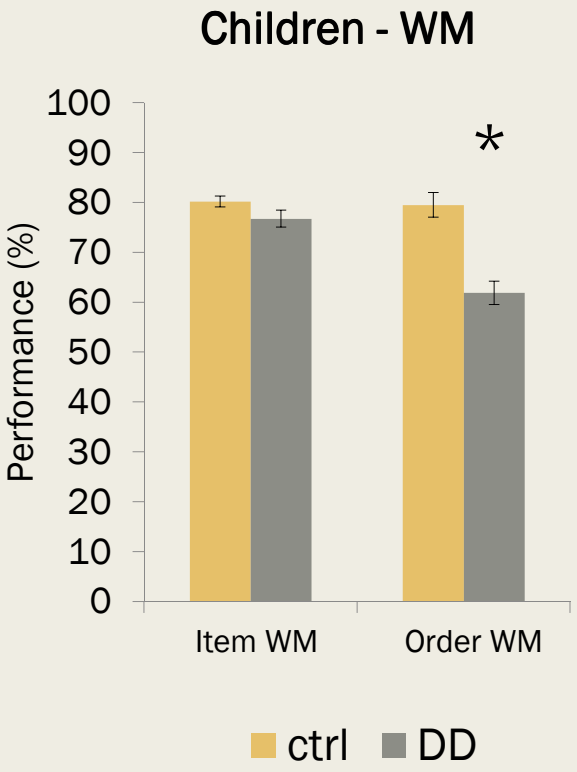
- N=108 8 year-old children



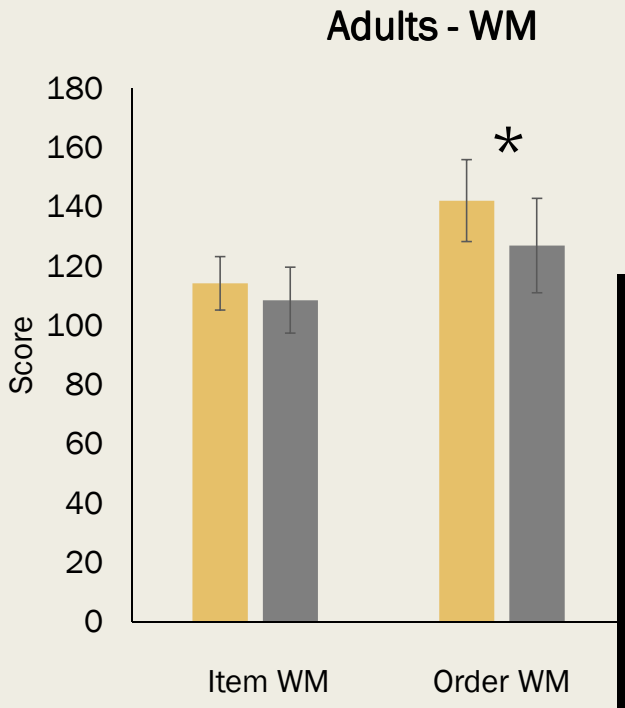
Attout & Majerus (2017). *BJDP*

Serial order WM & maths

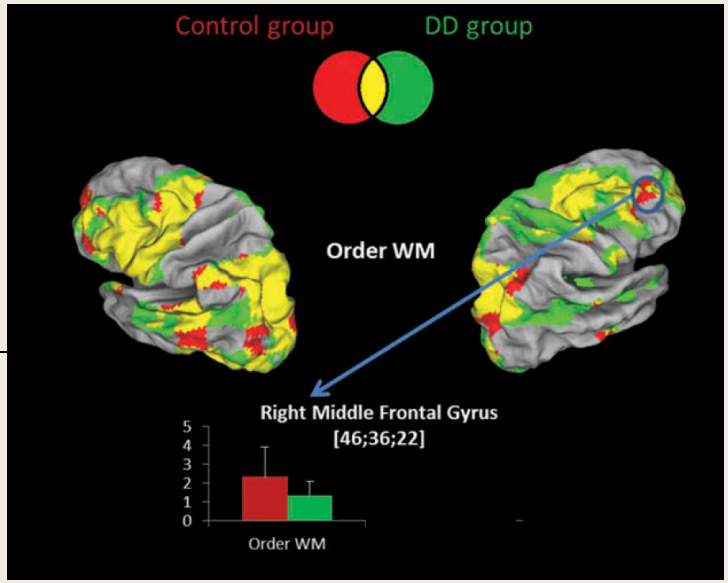




Attout & Majerus (2014). *Child Neuropsychology.*



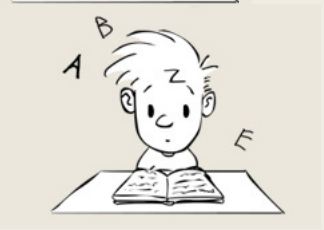
Attout, Salmon & Majerus (2015). *Developmental neuropsychology*



Serial order WM

?

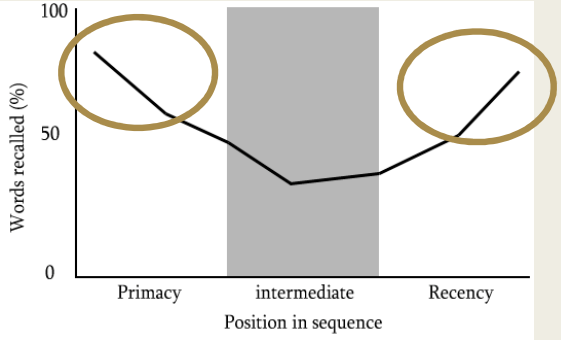
- Oral language
- Written language
- Math abilities



THE NATURE OF ORDER WM CODING

Order WM coding

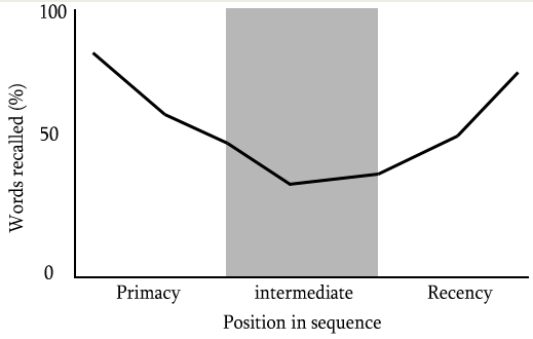
0 4 9 8 0 9 7 6 2 3



Ebinghaus, 1885; Avons, 1998; Guérard & Tremblay, 2008; Johnson et al., 2016; Lee & Estes, 1981; Smyth et al., 2005; Ward et al., 2005

Order WM coding

0 4 9 8 0 9 7 6 2 3



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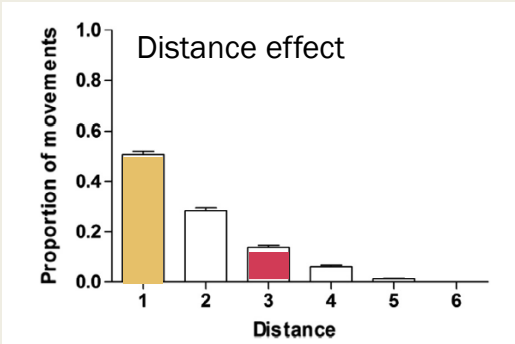
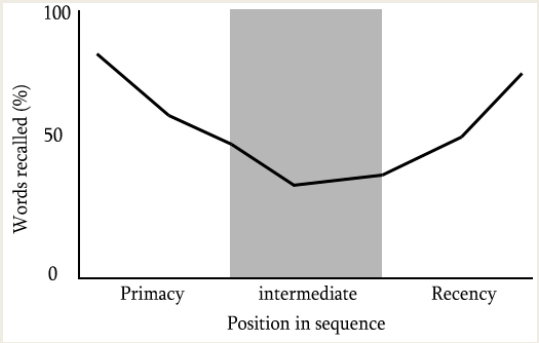


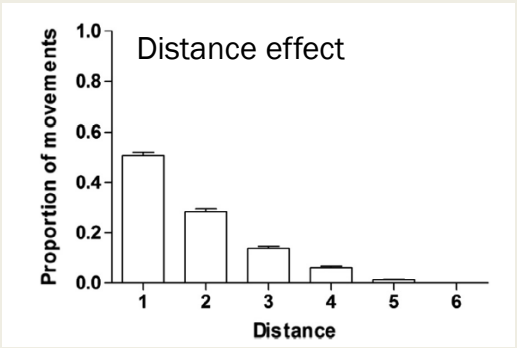
Burgess & Hitch, 1999; Henson; 1996; Hurlstone & Hitch, 2015; Parmentier et al., 2006

Order WM coding

0498-097-623

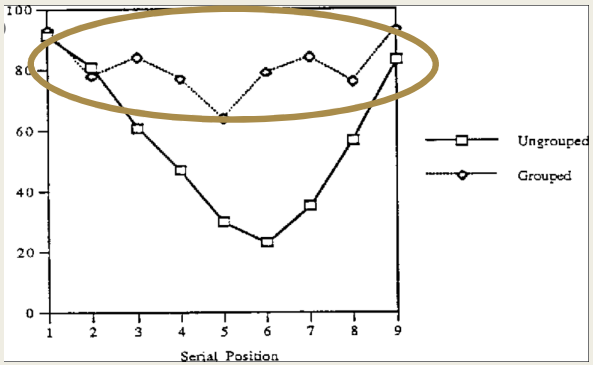


Ebinghaus, 1885; Avons, 1998; Guérard & Tremblay, 2008; Johnson et al., 2016; Lee & Estes, 1981; Smyth et al., 2005; Ward et al., 2005



Burgess & Hitch, 1999; Henson; 1996; Hurlstone & Hitch, 2015; Parmentier et al., 2006

Temporal grouping effect

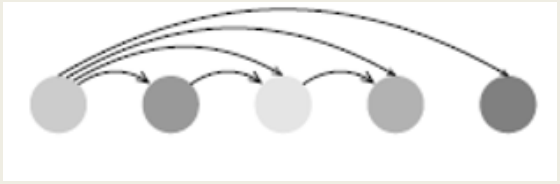


Deutsh, 1980; Frankish, 1985, Henson, 1996; Hitch et al., 1996; Parmentier et al., 2004; 2006

Several computational models exist but no one can reproduce the entire behavioral effects usually seen in order WM processing

Order WM models

Chaining models



Can explain only a limited range of behavioral effects

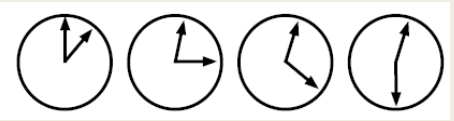
Positionnal models

Can explain very succesfully a large panel of behavioral effects

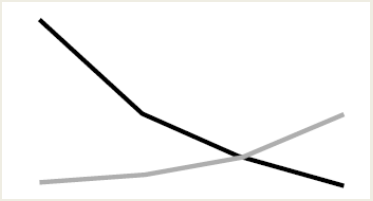
Order WM models

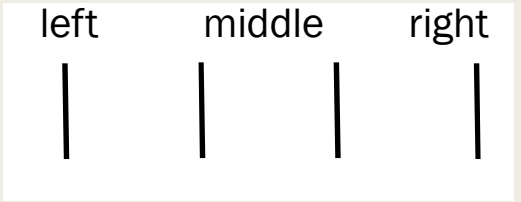
Positionnal models

Temporal markers (oscillatory response) (Brown et al., 2000)

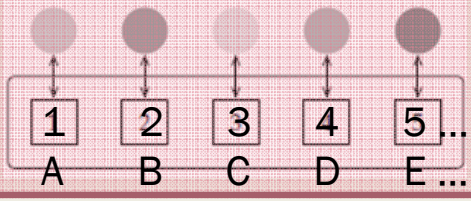


Spatial markers (Start-end, Henson, 1998; Abrahamse et al., 2014)

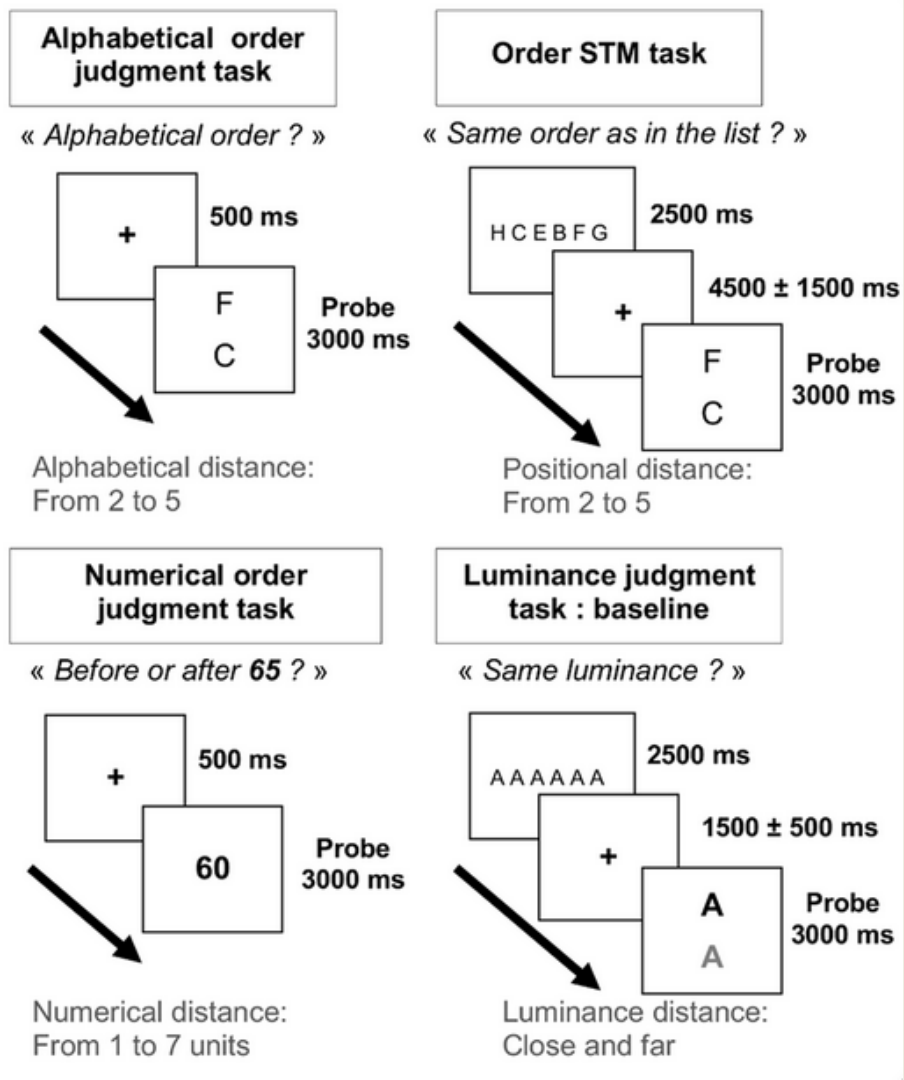


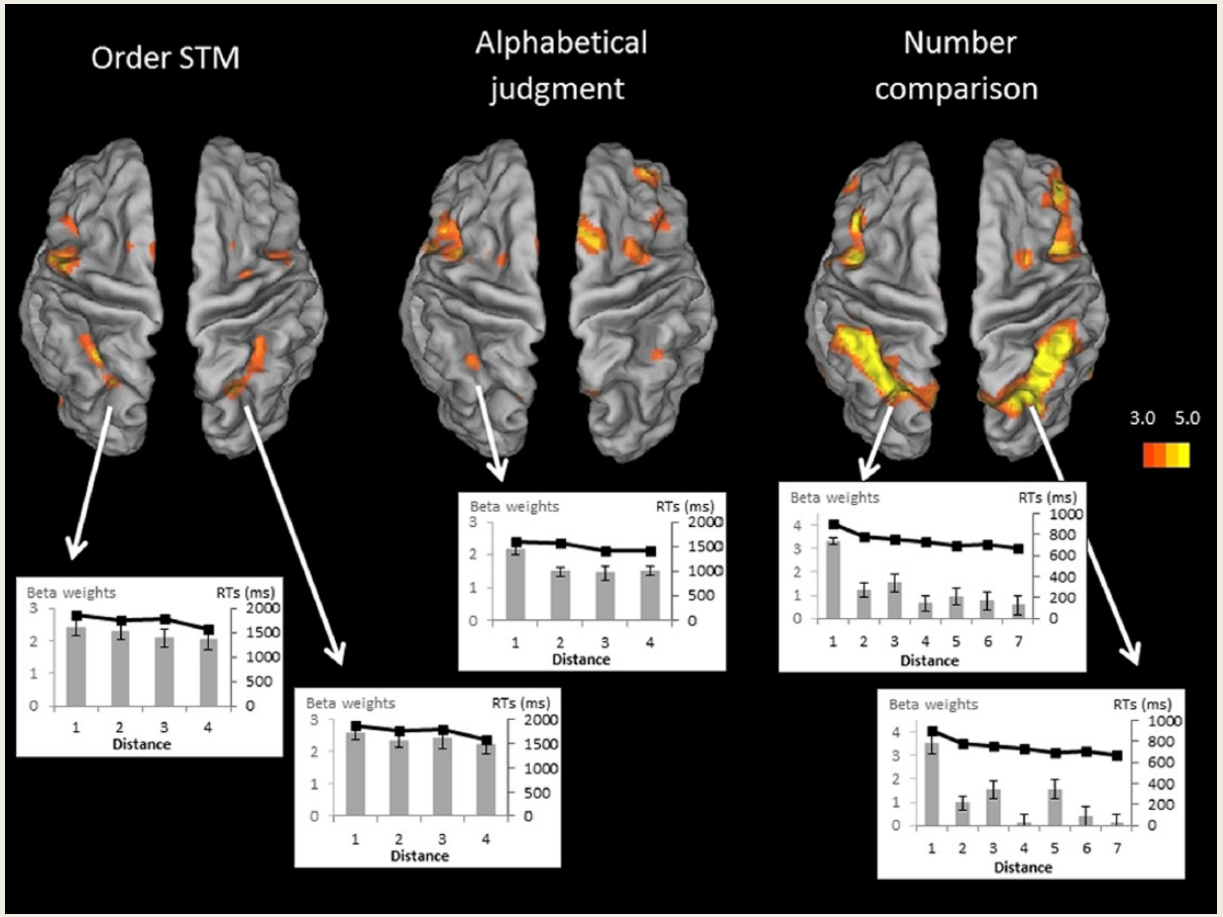


Rank markers (Botvinick & Watanabe, 2007)



Common ordinal representation ?





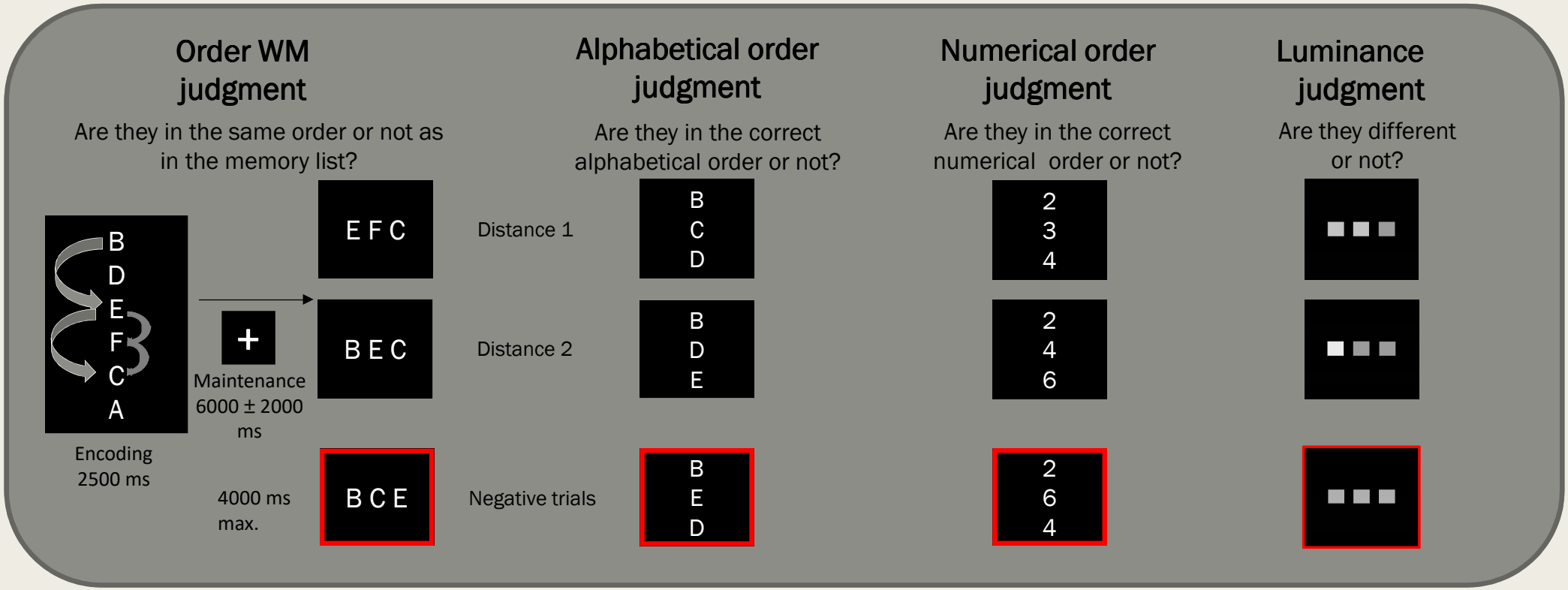
→ a more general, common ordinal representation to code serial order in WM
BUT similar brain networks ≠ same information is processed

Attout, Fias, Salmon, Majerus (2014). Plos One

Common ordinal representation ?

MVPA + triplets

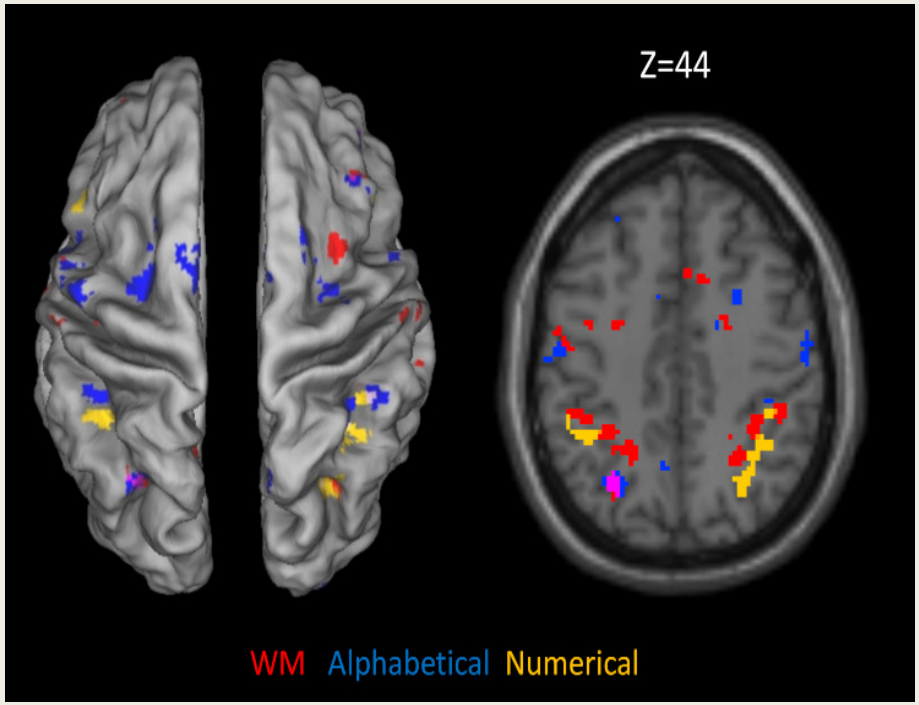
→ examining patterns of neural responses, rather than analyzing single voxel or regions
→ more robust way to assess distance effect



Attout, Leroy, & Majerus, 2021, Cerebral Cortex

Common ordinal representation ?

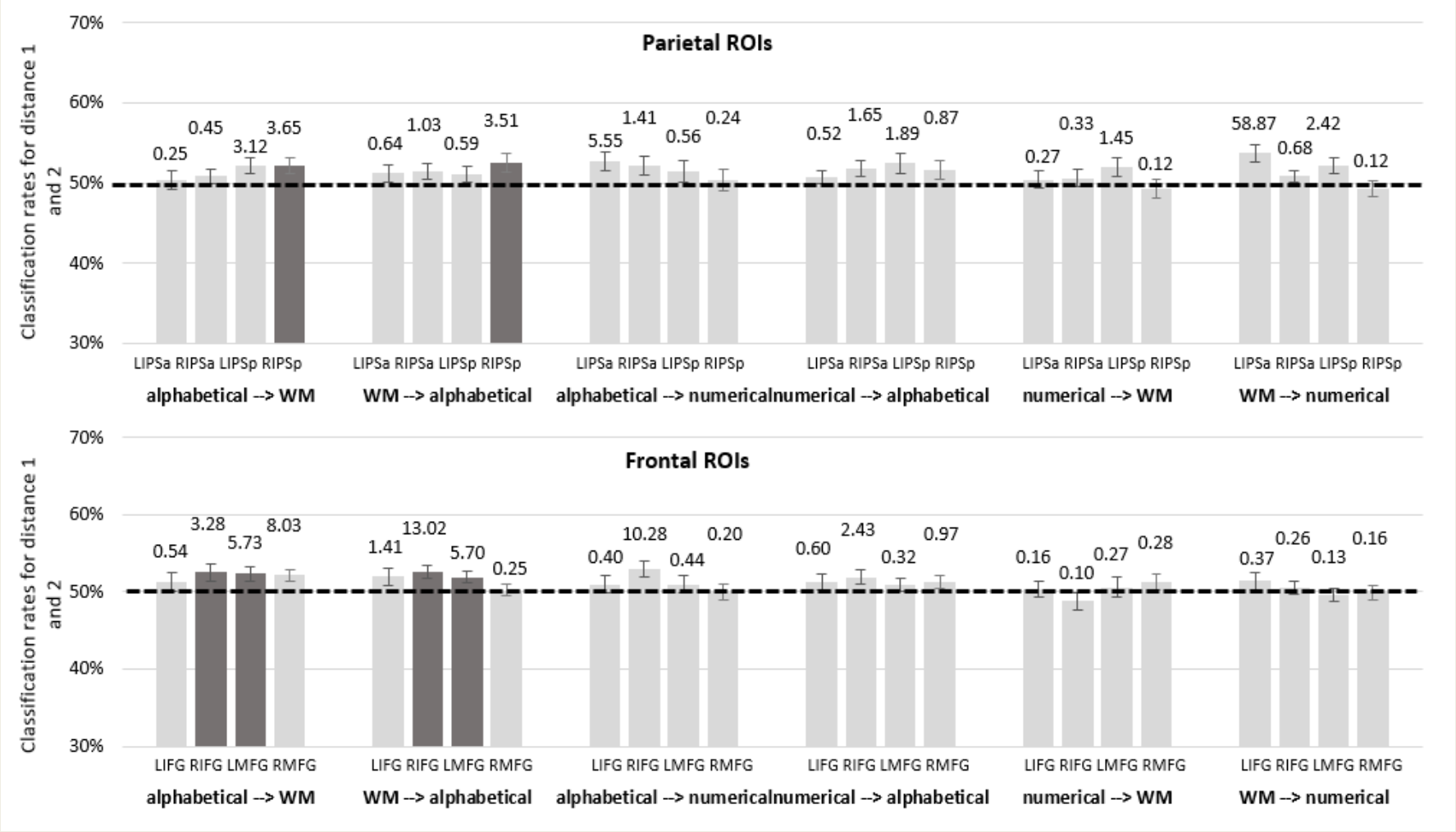
- Univariate



	No. voxels	Left/ right	x	y	z	SPM Z - value
Ordinal distance effect for order WM (D2<D1)						
IPSa	26	L	-30	-44	44	3.79*
	50	R	46	-36	40	4.25*
IPSp	96	L	-28	-64	44	4.26*
Ordinal distance effect for ordinal alphabetical judgment (D2<D1)						
IPSp	43	L	-28	-64	44	4.24*
	11	R	30	-62	38	3.50*
Ordinal distance effect for ordinal numerical judgment (D2<D1)						
IPSa	69	L	-38	-44	40	3.81*
	28	R	38	-38	40	3.73*
IPSp	71	R	32	-60	46	4.00*
MFG	57	L	-48	22	22	3.98*
	18	R	46	40	22	3.89*
IFG	34	L	-36	28	20	4.06*
Standard distance effect for luminance judgment (D1<D2)						
BA17	6	R	16	-94	-4	3.57[a]

Common ordinal representation ?

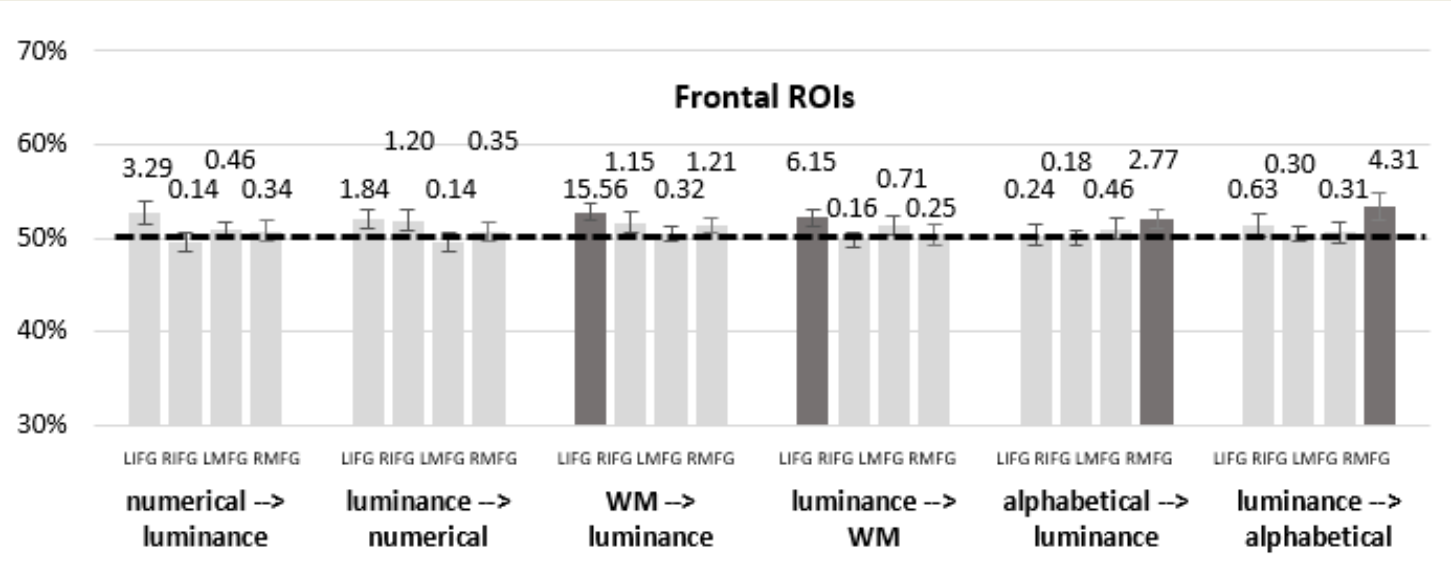
MVPA Prediction between tasks



Common ordinal representation ?

Prediction between tasks

With **luminance judgment**



→ this frontal involvement was not specific to the ordinal processing but more general

Common ordinal representation ?

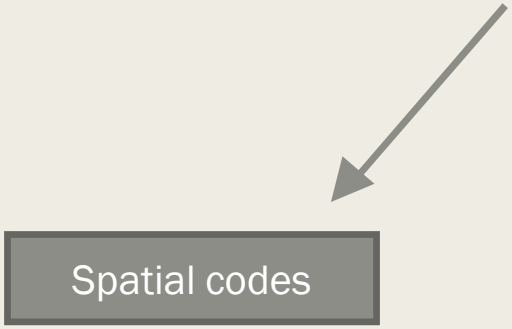
- Domain-general implication of fronto-parietal cortices BUT do not support the hypothesis of domain-general ordinal codes per se
  - *prediction of ordinal distance only for the order WM and alphabetical tasks, but not for the numerical domain*
  - *prediction not specific to ordinal distance → luminance distance*

'hard-vs-easy' dimension → different levels of attentional control

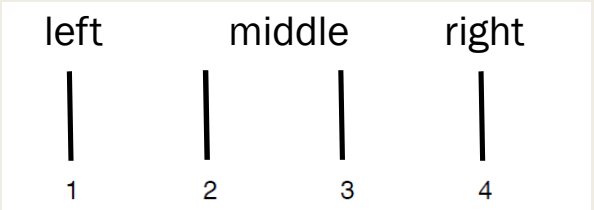
- More specific role of the posterior IPS for ordinal processing ?
- A spatial-attentional role of the posterior IPS
  - *Differentiated neural signals for leftward versus rightward orientation of attention (Yantis et al. 2002; Silver and Kastner 2009; Vandenberghe and Gillebert 2009; Bressler and Silver 2010; Gillebert et al. 2011).*
  - *Mental whiteboard hypothesis : attentional spatial frame could allow the temporary organisation of memoranda and letters on a horizontal line, ordered from left to right (Abrahamse et al. 2014, 2017)*

Role of spatial or temporal representation in order WM

Positional models



Henson, 2000; Abrahamse et al., 2017; Van Dijck et al., 2011; Guida

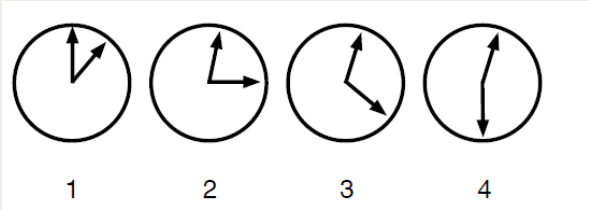


Role of spatial or temporal representation in order WM

Positional models

Temporal codes

Hartley, Hurlstone and Hitch, 2016; Brown et al. 2000



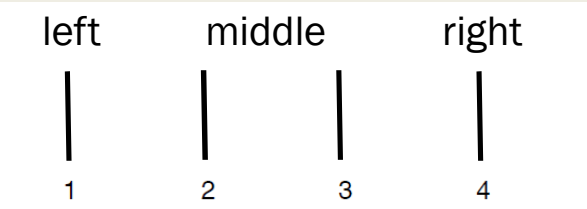
Role of spatial or temporal representation in order WM

Positional models

?

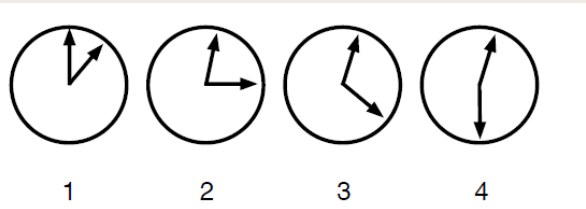
Spatial codes

Henson, 2000; Abrahamse et al., 2017; Van Dijck et al., 2011; Guida



Temporal codes

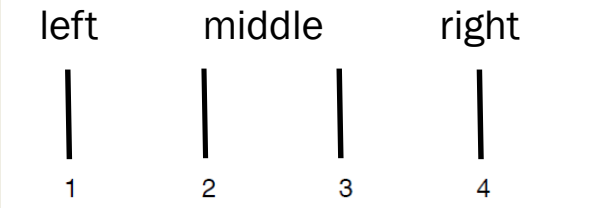
Hartley, Hurlstone and Hitch, 2016; Brown et al. 2000



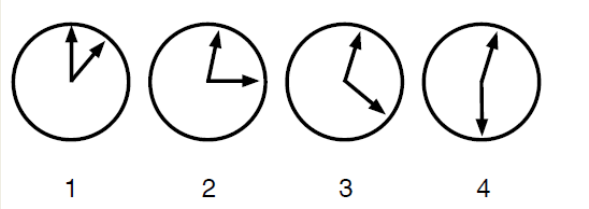
Role of spatial or temporal representation in order WM

fMRI study

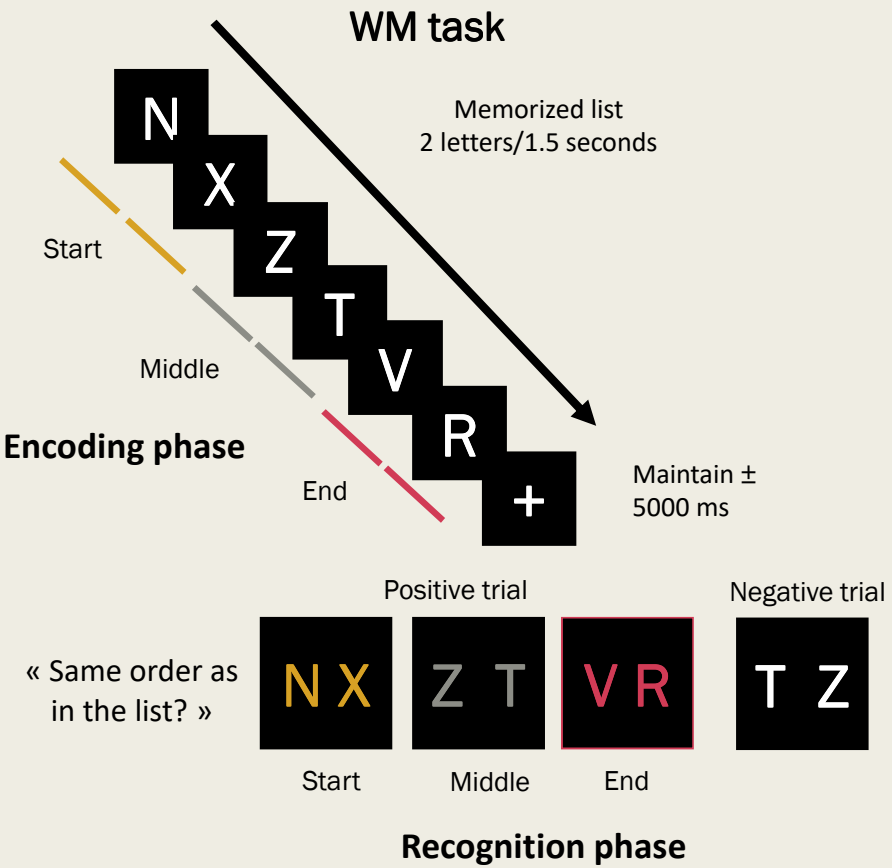
- commonality of the spatial attention and WM representations

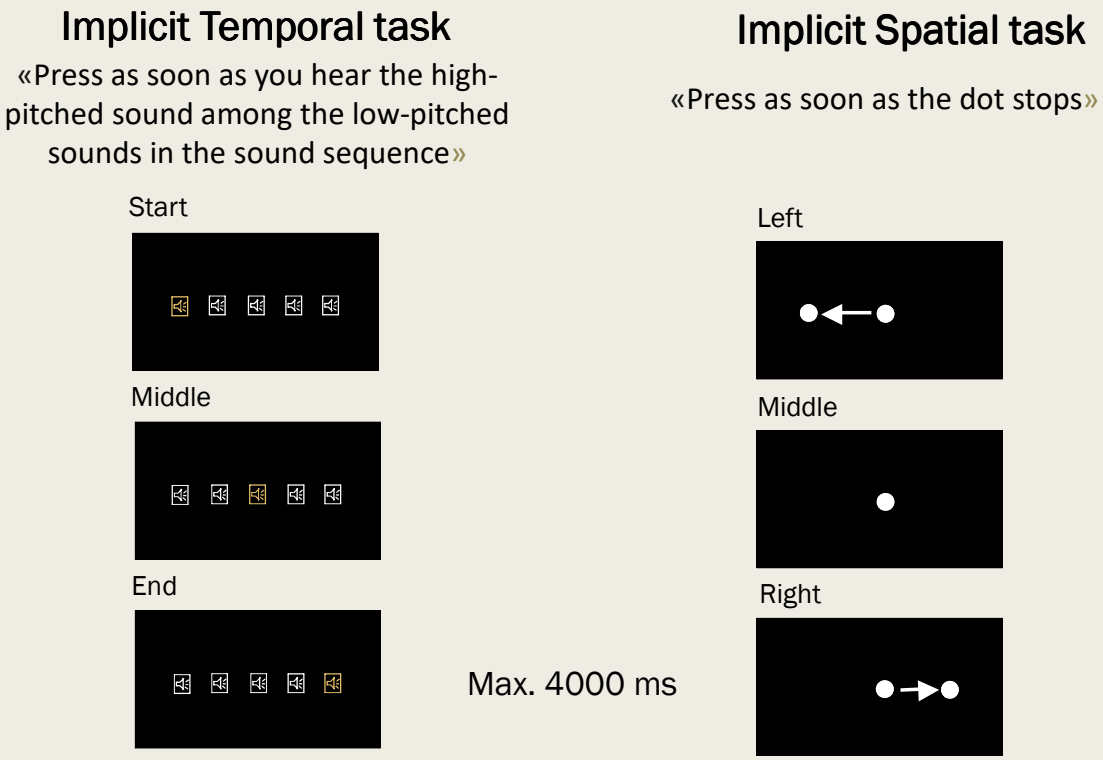


- commonality of the temporal attention and WM representations



Role of spatial or temporal representation in order WM

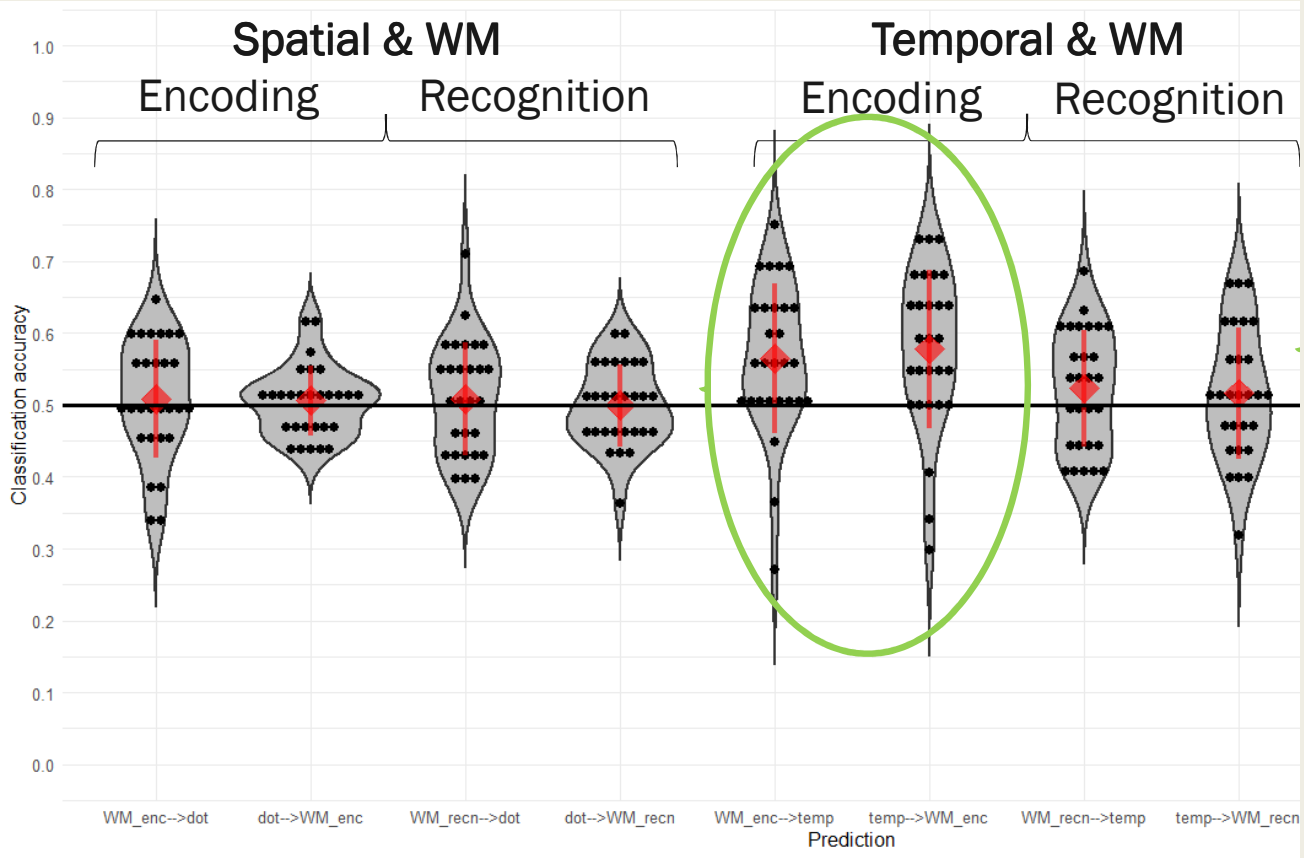




For all Tasks : Start/Left vs. End/Right

Role of spatial or temporal representation in order WM

Prediction between spatial/temporal tasks & the WM task (for encoding and recognition) for the classification between start-of-list/left VS end-of-list/right

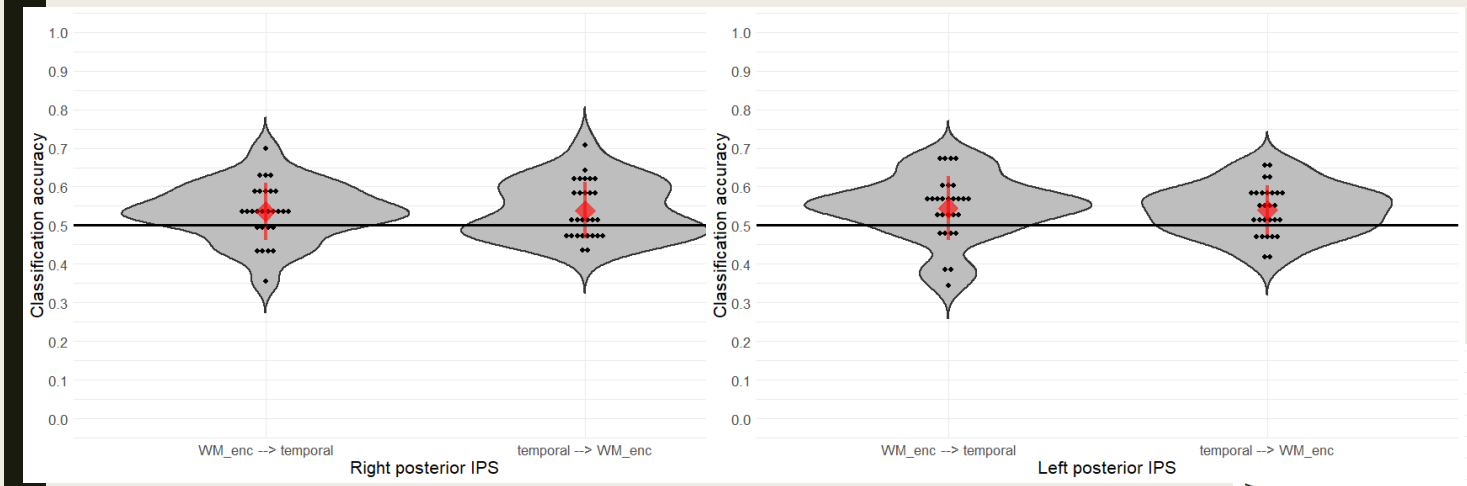


Bayesian One Sample T-Test

	BF_{+0}
dot_temp_fold1_37	0.217
dot_temp_fold2_38	0.361
WM_enc_dot_fold1_39	0.317
WM_enc_dot_fold2_40	0.358
WM_recn_dot_fold1_41	0.332
WM_recn_dot_fold2_42	0.191
WM_enc_temp_fold1_43	25.890
WM_enc_temp_fold2_44	76.568
WM_recn_temp_fold1_45	1.009
WM_recn_temp_fold2_46	0.478
WM_enc_recn_fold1_47	1.381e +6
WM_enc_recn_fold2_48	3957.313

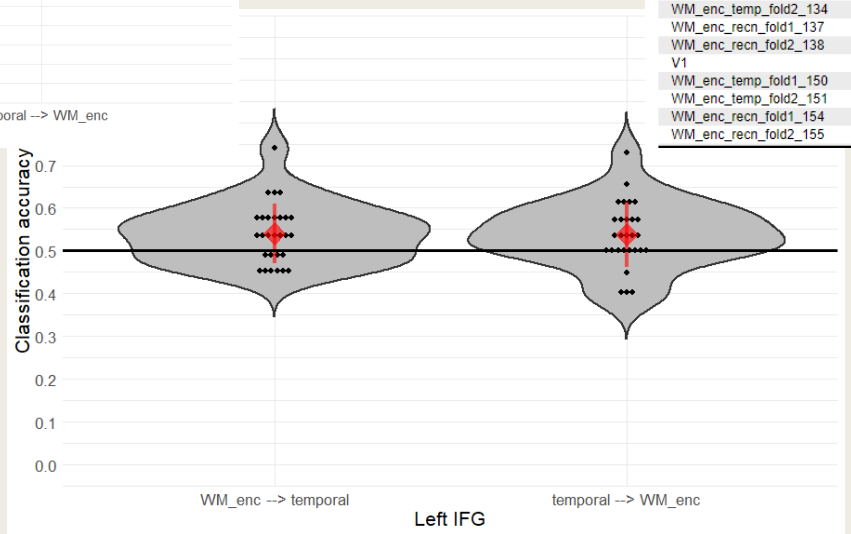
Role of spatial or temporal representation in order WM

Prediction between **temporal** and the **WM tasks** (for encoding) for ROIs (IPSa; IPSp; IFG; MFG; V1)



Bayesian One Sample T-Test

	BF_{+0}
RISPA	NaN[a]
WM_enc_temp_fold1	0.461
WM_enc_temp_fold2	1.048
WM_enc_recn_fold1	60.715
WM_enc_recn_fold2	18.925
LIPSA	NaN[b]
WM_enc_temp_fold1_31	0.825
WM_enc_temp_fold2_32	15.558
WM_enc_recn_fold1_35	495.677
WM_enc_recn_fold2_36	2.029
RIPSP	NaN[d]
WM_enc_temp_fold1_48	5.699
WM_enc_temp_fold2_49	10.625
WM_enc_recn_fold1_52	13.039
WM_enc_recn_fold2_53	77.031
LIPSP	NaN[e]
WM_enc_temp_fold1_65	10.290
WM_enc_temp_fold2_66	23.272
WM_enc_recn_fold1_69	28.511
WM_enc_recn_fold2_70	33.919
RIFG	NaN[f]
WM_enc_temp_fold1_82	0.201
WM_enc_temp_fold2_83	2.180
WM_enc_recn_fold1_86	475.948
WM_enc_recn_fold2_87	45.646
LIFG	NaN[g]
WM_enc_temp_fold1_99	18.358
WM_enc_temp_fold2_100	6.472
WM_enc_recn_fold1_103	18.335
WM_enc_recn_fold2_104	60.183
RMFG	NaN[h]
WM_enc_temp_fold1_116	0.304
WM_enc_temp_fold2_117	2.874
WM_enc_recn_fold1_120	2.194
WM_enc_recn_fold2_121	36.834
LMFG	NaN[i]
WM_enc_temp_fold1_133	1.611
WM_enc_temp_fold2_134	24.011
WM_enc_recn_fold1_137	5.782
WM_enc_recn_fold2_138	84.602
V1	NaN[j]
WM_enc_temp_fold1_150	0.193
WM_enc_temp_fold2_151	0.226
WM_enc_recn_fold1_154	28.411
WM_enc_recn_fold2_155	122.756



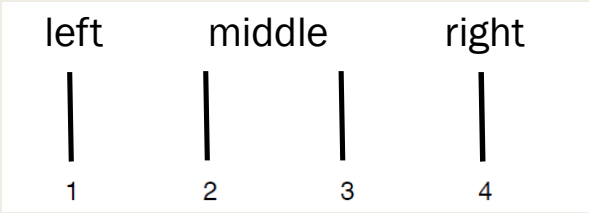
--> posterior IPS (bilaterally) & Left IFG

Role of spatial or temporal representation in order WM

Positional models

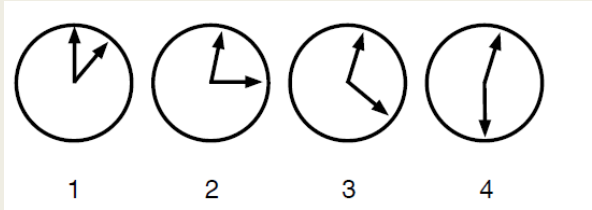
Spatial codes

Henson, 2000; Abrahamse et al., 2017; Van Dijck et al., 2011; Guida



Temporal codes

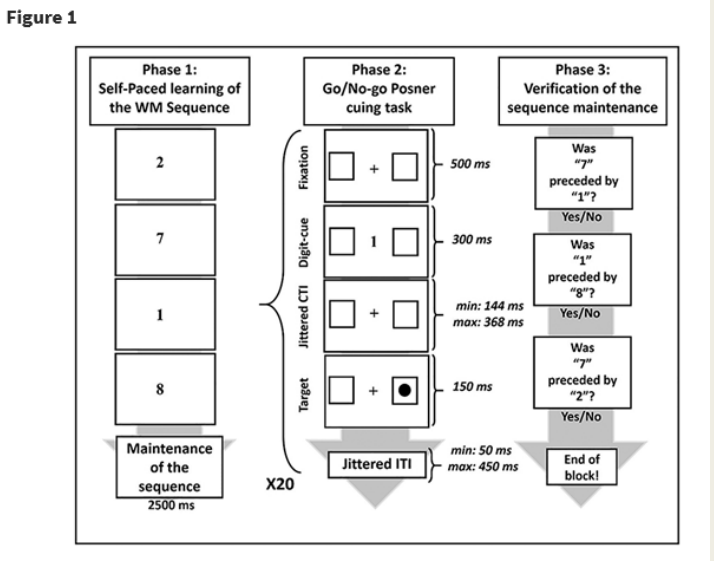
Hartley, Hurlstone and Hitch, 2016; Brown et al. 2000



Discussion

- This needs to be reproduce in other context
- Spatial codes more for the serial order LTM processes
- Spatialization is flexible → more like a strategy than a coding per se

Henson, 2000; Abrahamse et al., 2017; Van Dijck et al., 2011; Guida; Rasoulzadeh et al., 2021



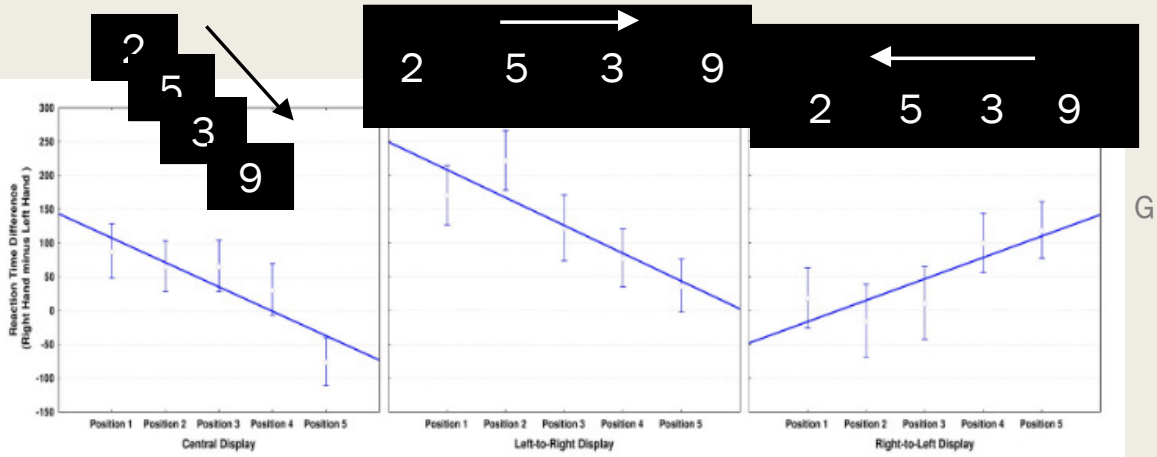


Figure 2. Observed data and regression line representing right-hand reaction times minus left-hand reaction times as a function of *position in the sequence* that was probed (five positions) and *items presentation*.

Guida et al., 2020

Interim conclusions

- Serial order WM required **domain-general coding** but not necessarily a more general ordinal representation per se
- This domain-general coding could be **sustained by a temporal coding** engrained in the posterior IPS and the IFG.
- However, to maintain and recall the information, serial order WM could be represented spatially to be manipulated and recalled more easily.

→ Further research needs to be done to understand this specificity of spontaneous vs. strategic coding of information.

Conclusion

- Inportance to take into account the serial order level in WM and to understand the nature of this coding
- Important to identify precisely the WM deficits to accurately deal with them
- Required to consider the treatment/training of order WM in children with learning disabilities and brain-damaged patients

THANK YOU FOR YOUR ATTENTION

Steve Majerus

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