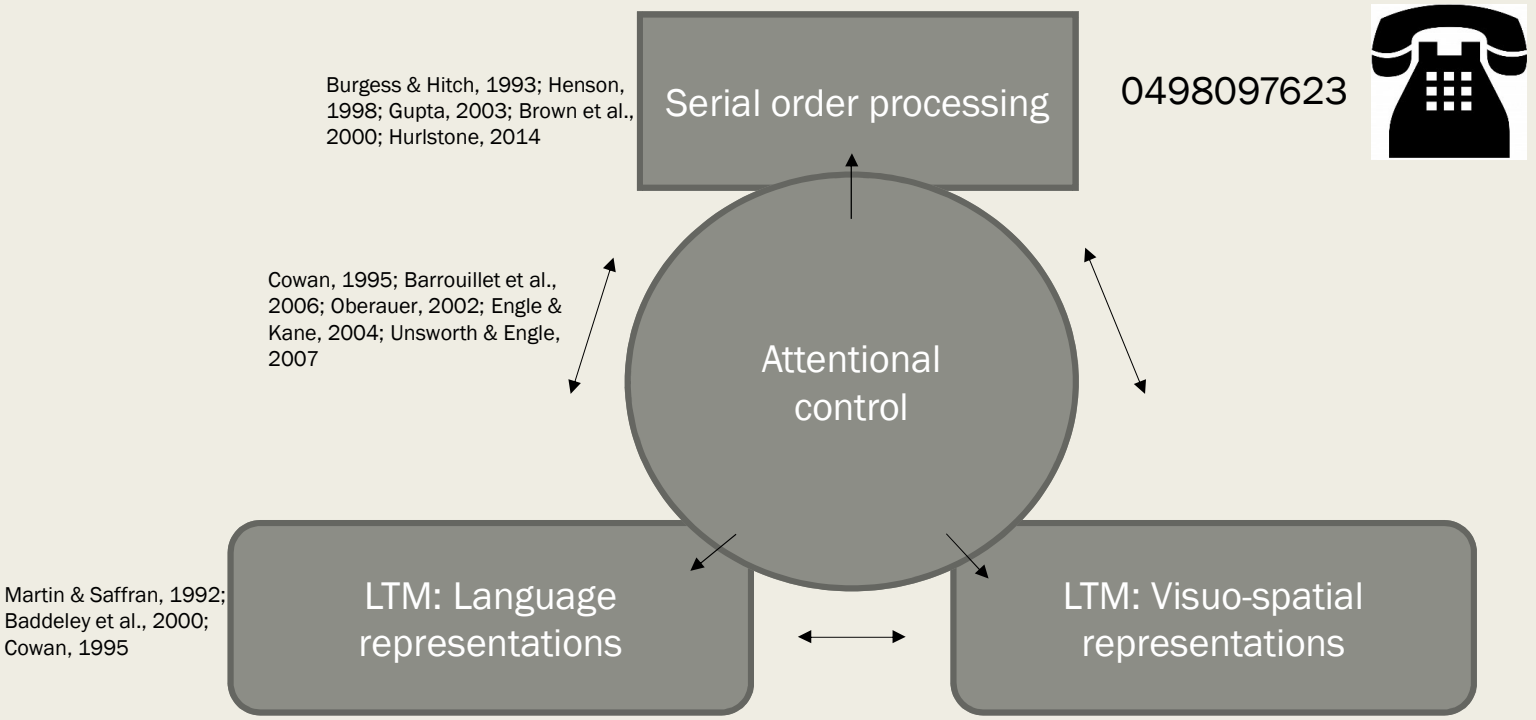
IS IT A MATTER OF TIME OR SPACE TO CODE SERIAL ORDER IN WORKING MEMORY?

Lucie Attout, Robin Remouchamps & Steve Majerus, University of Liège, Belgium

ESCOP 2022, Lille

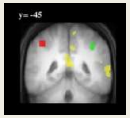
Working memory = capacity to temporarily maintain information in mind and to mentally manipulate it during a short period when we want to reach a specific goal (Cowan & Alloway, 2009).



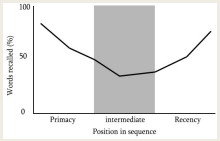
Hurlstone et al., 2014; Majerus, 2013; Oberauer, 2009; Barrouillet & Camos, 2014

Serial order WM

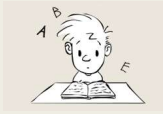
- Specific and independent component (Majerus et al., 2006; 2010; 2017; 2018; Attout et al., 2012, 2018)



- Link to strategic aspects (grouping, primacy and recency effect,…)



- Crucial in a series of learning abilities (oral and written language; math abilities) (Majerus et al., 2006; 2008; 2013; Leclercq & Majerus, 2010; Martinez Perez et al., 2012; Attout et al., 2014; 2018; 2020)

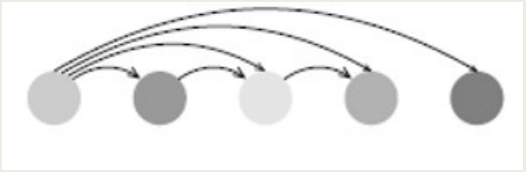


- Important way to consolidate information at long-term (Hebb; e.g. Ordonez Magro, Attout, Majerus, & Szmalec, 2018)

Serial order WM models

Chaining models

cue for the next item



Can explain only a limited range of behavioral effects

Positionnal models

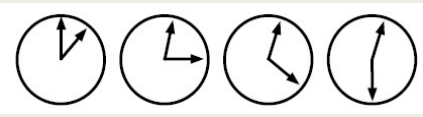
reference system

Can explain very succesfully a large panel of behavioral effects

Serial order WM models

Positionnal models

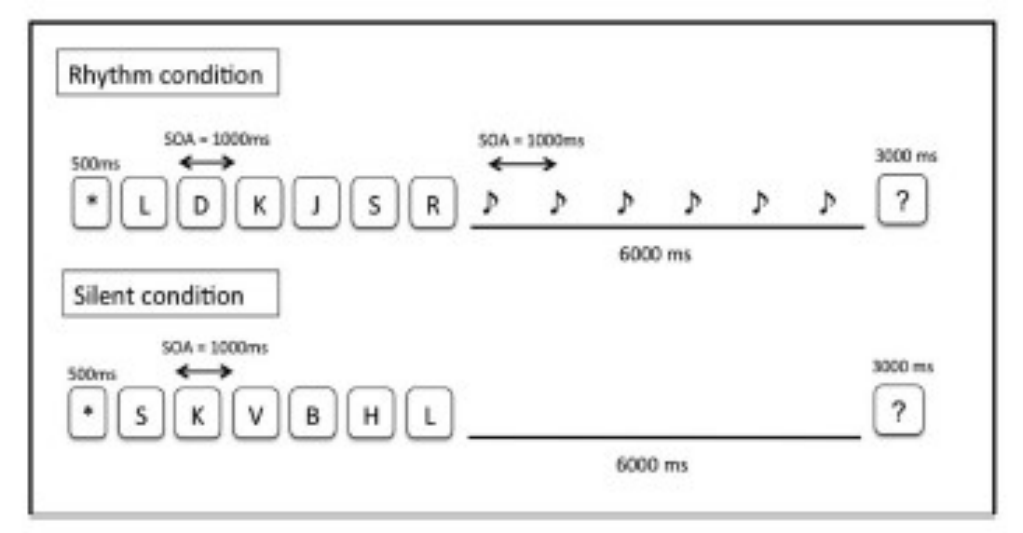
Temporal markers (oscillatory response)
(Brown et al., 2000; Hartley et al., xxx)

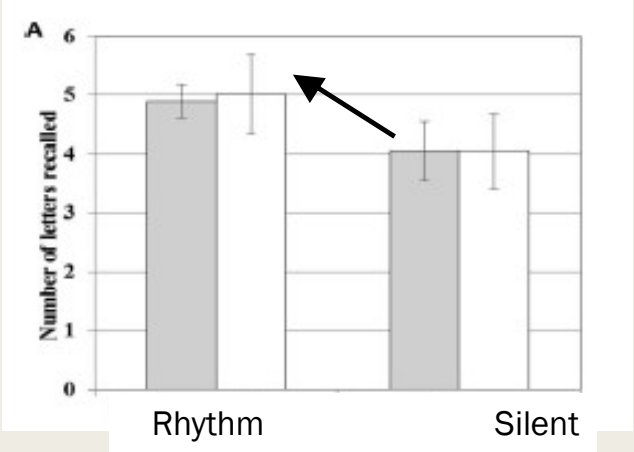


Serial order WM

Temporal codes

Plancher et al., 2017; Henson et al., 2003

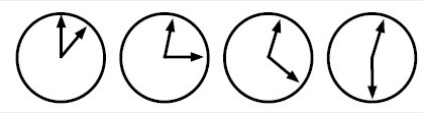




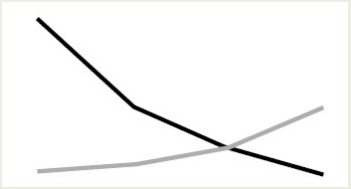
Serial order WM models

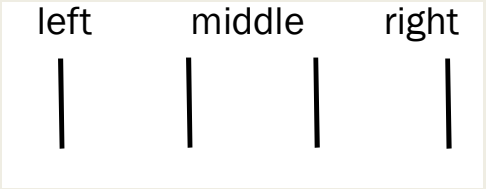
Positionnal models

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



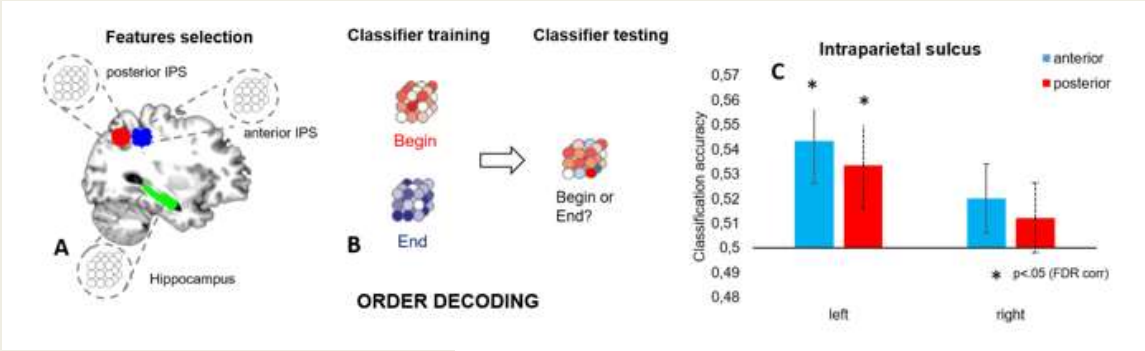
Spatial markers
(Start-end, Henson, 1998; Abrahamse et al., 2014; Van Dijck et al., 2011; Guida et al., xxx)



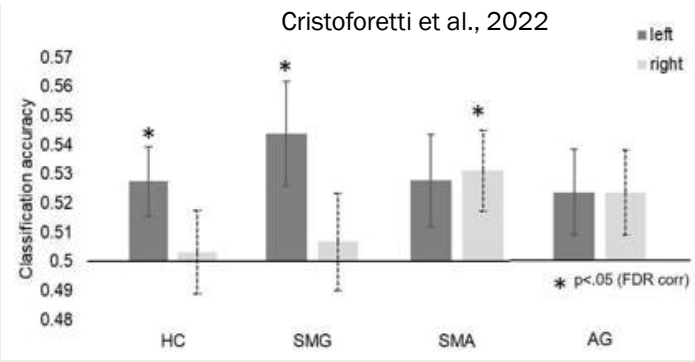


Serial order WM

Spatial codes



Cristoforetti et al., 2022



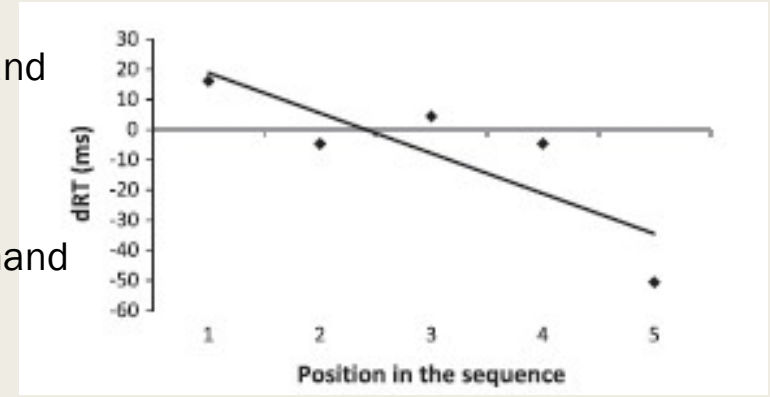
Phase 1: Encoding
3-7-1-4-9

Phase 2 : Maintenance
Go/no go task
2? 3? 8? 9?

Phase 3: Recall

Left hand

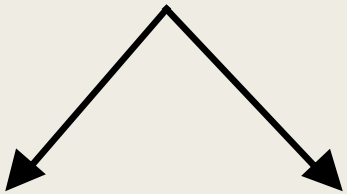
Right hand



Van Dijck & Fias, 2011
Rasoulzadeh et al., 2021

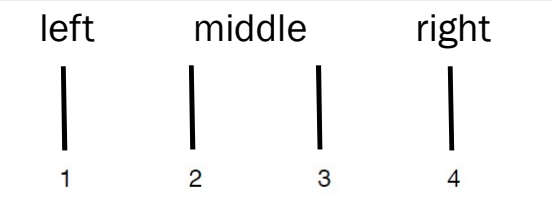
Research question

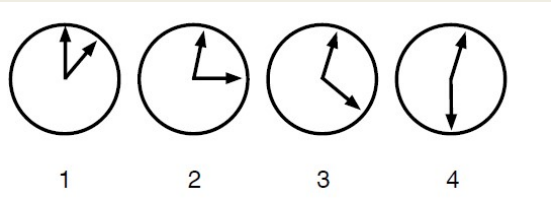
Serial order WM



Spatial codes

Temporal codes



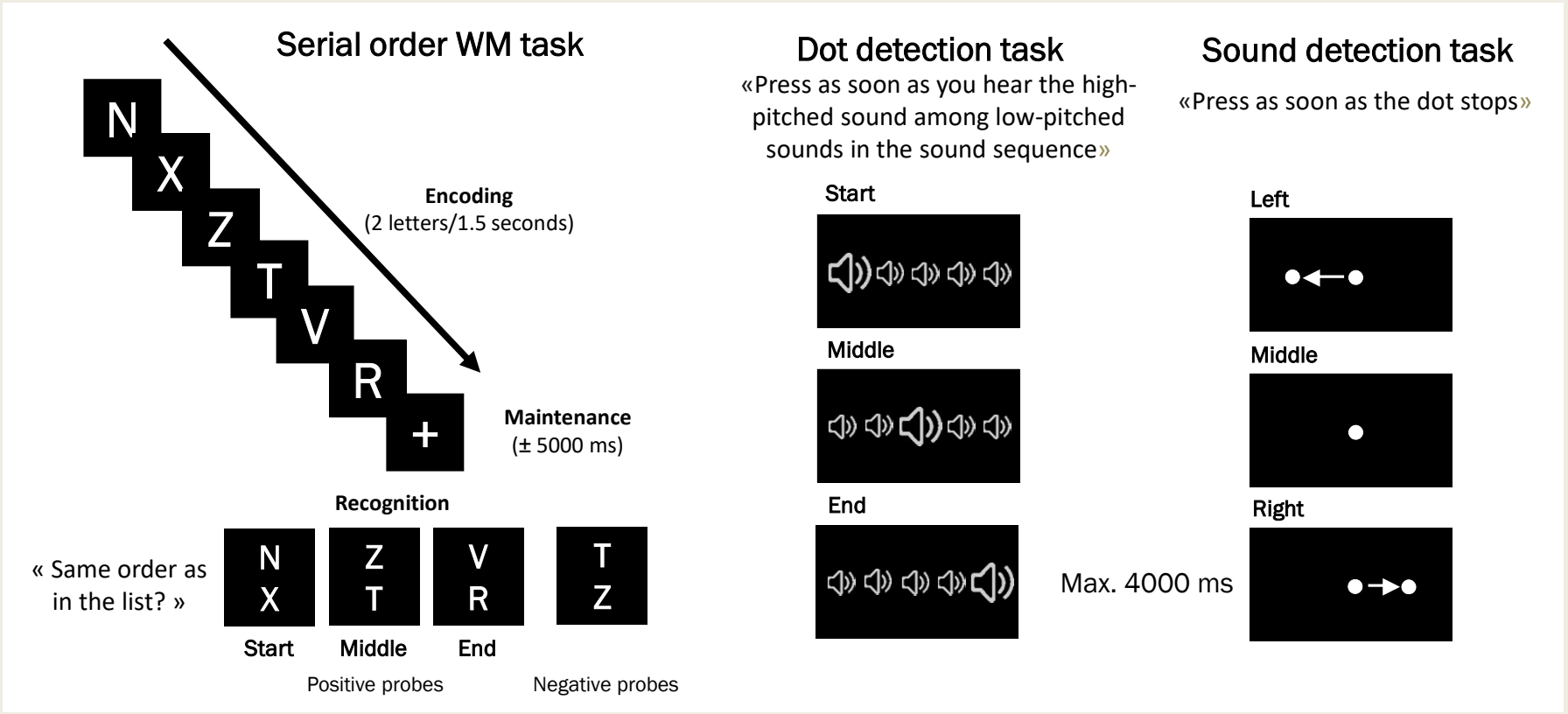


commonality of the spatial attention and WM representations

commonality of the temporal attention and WM representations

Method

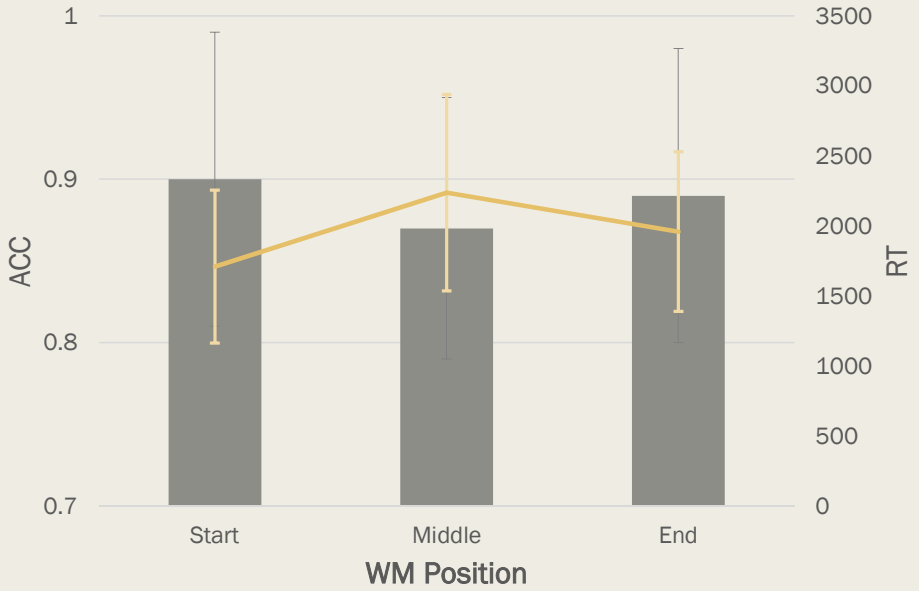
Participants : 28 participants (17 women) (mean age = 22.41 ± 3.06 years old, age range = 18-30).



+ An Eye tracking was used to record the eye-movements at 1000 Hz during the serial order WM task in the scanner.

Behavioral results

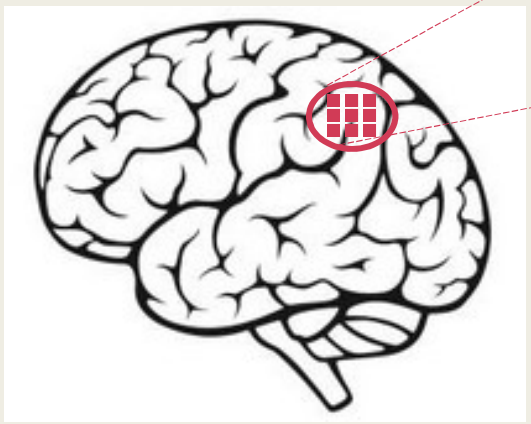
Bayesian repeated measures ANOVA (Positions: start-middle-end)

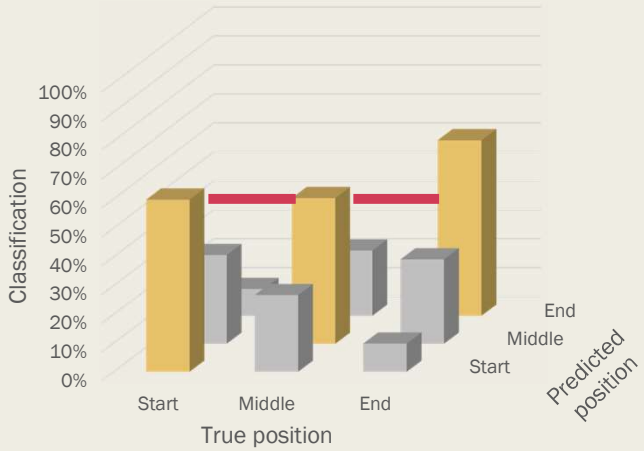


ACC: anecdotal evidence in favour of the positional effect (BF_{10}=0.38)

RT: decisive evidence for a positional effect (BF_{10}=55754.75)

MVPA analyses

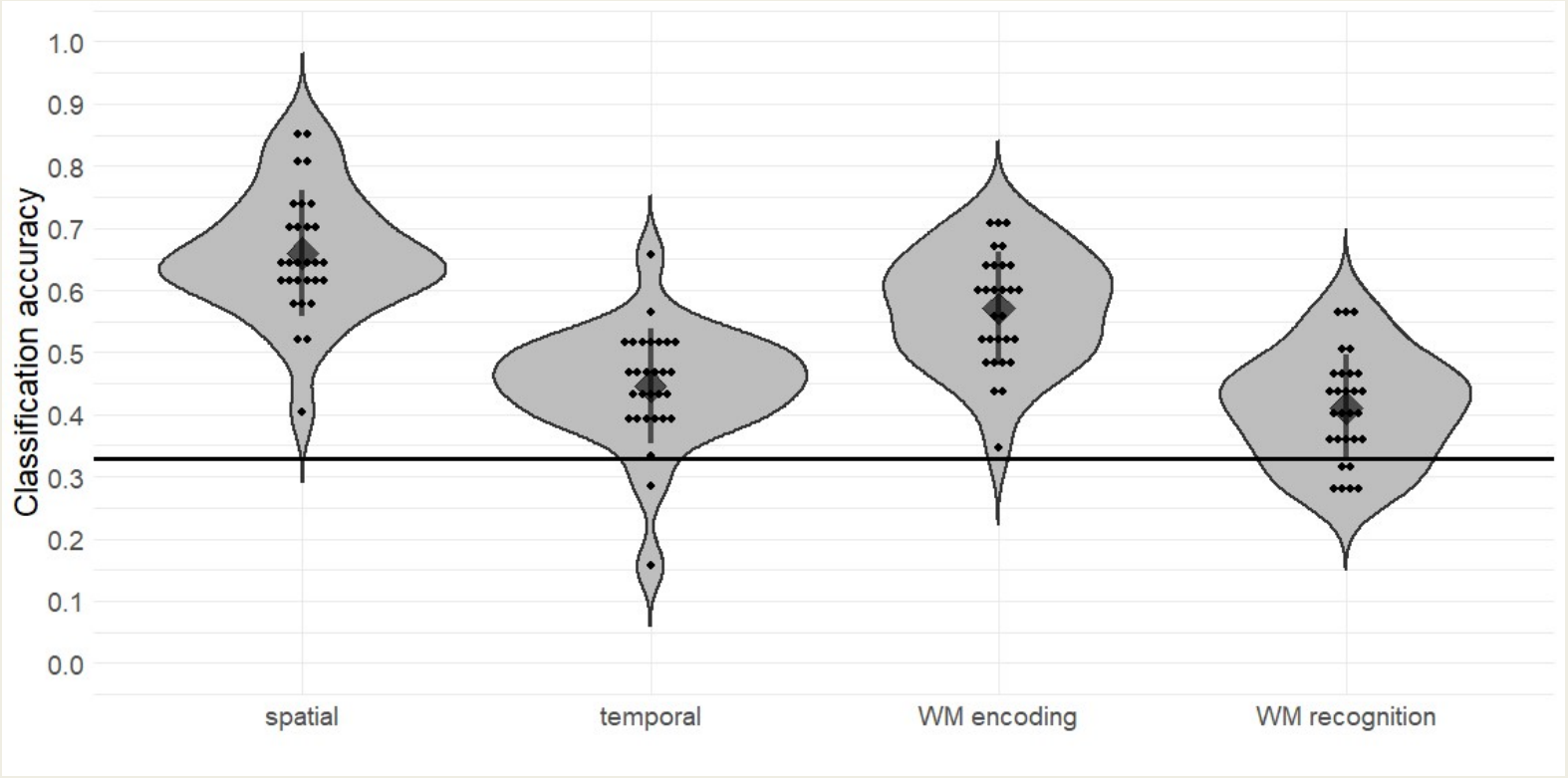




Within: Intra-task

Between : Inter-task

fMRI Results : classification intra-task Whole-brain

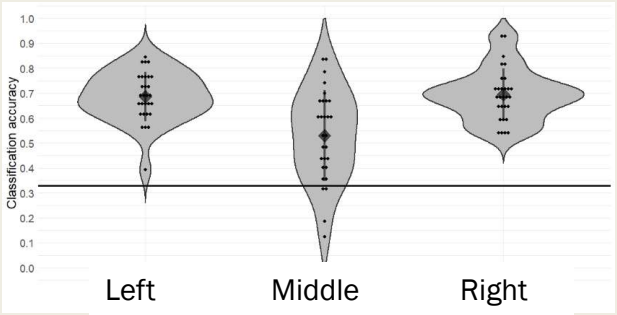


BF_{10}= 9.11^{E}+13 BF_{10}= 1.46^{E}+5 BF_{10}= 5.93^{E}+11 BF_{10}= 2.24^{E}+3

ROI : preMC; IFG; MFG; IPSap; SMA; LSMG

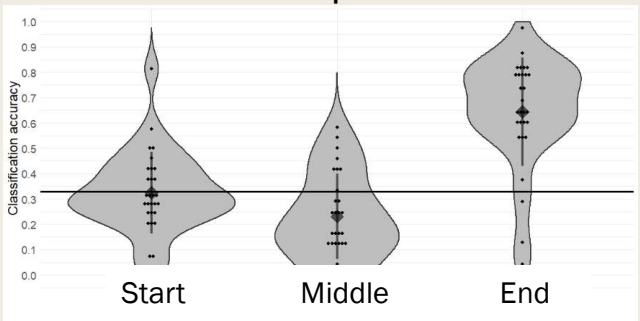
fMRI Results : classification intra-task Whole-brain

Spatial



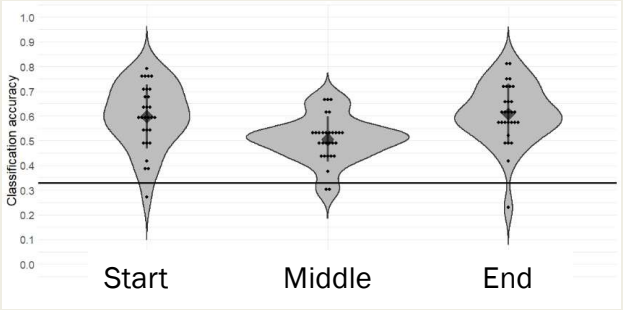
BF_{10}= 1.16^{E}+15 BF_{10}= 1.52^{E}+4 BF_{10}= 4.12^{E}+14

Temporal



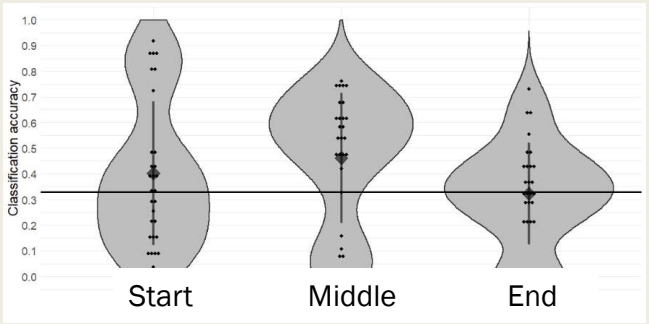
BF_{10}= 0.17 BF_{10}= 0.06 BF_{10}= 2.12^{E}+6

WM encoding



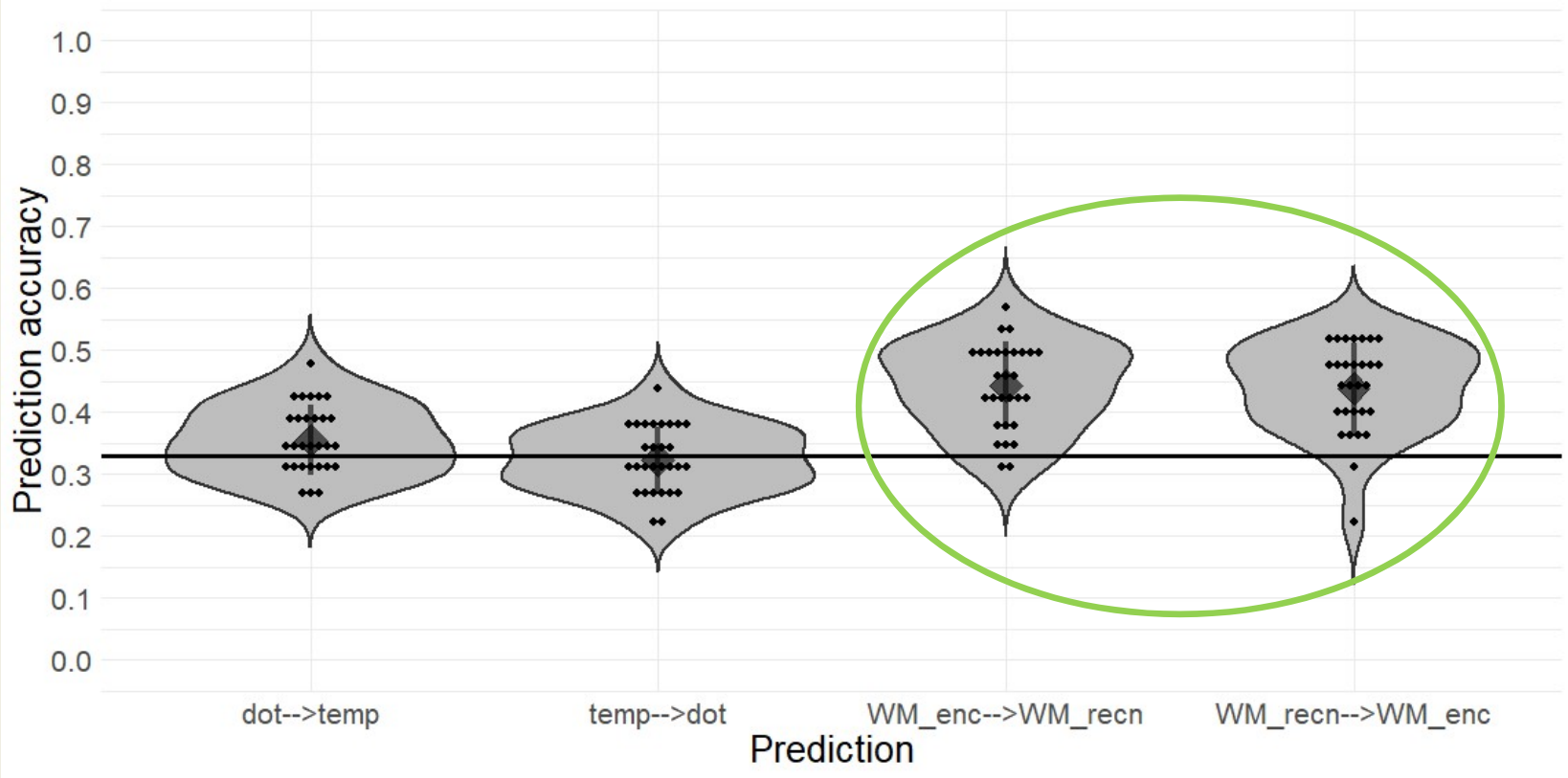
BF_{10}= 1.92^{E}+9 BF_{10}= 4.24^{E}+8 BF_{10}= 1.42^{E}+10

WM recognition



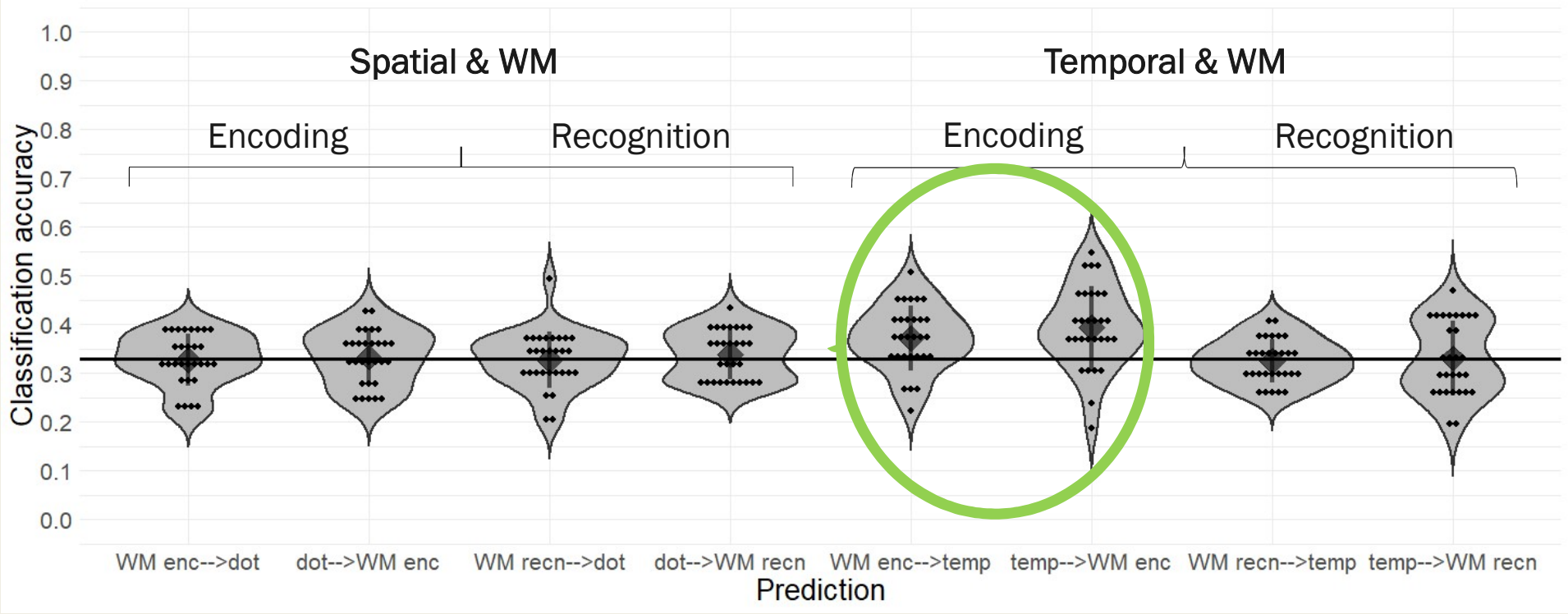
BF_{10}= 0.83 BF_{10}= 9.47 BF_{10}= 0.17

fMRI Results : prediction inter-task Whole-brain



BF_{10}= 4.17 BF_{10}= 0.13 BF_{10}= 8.70 E+6 BF_{10}= 2.16 E+6

fMRI Results : classification inter-task Whole-brain



BF_{10}= 0.16 BF_{01}= 6.25

BF_{10}= 0.25 BF_{01}= 4

BF_{10}= 0.16 BF_{01}= 6.25

BF_{10}= 0.44 BF_{01}= 6.25

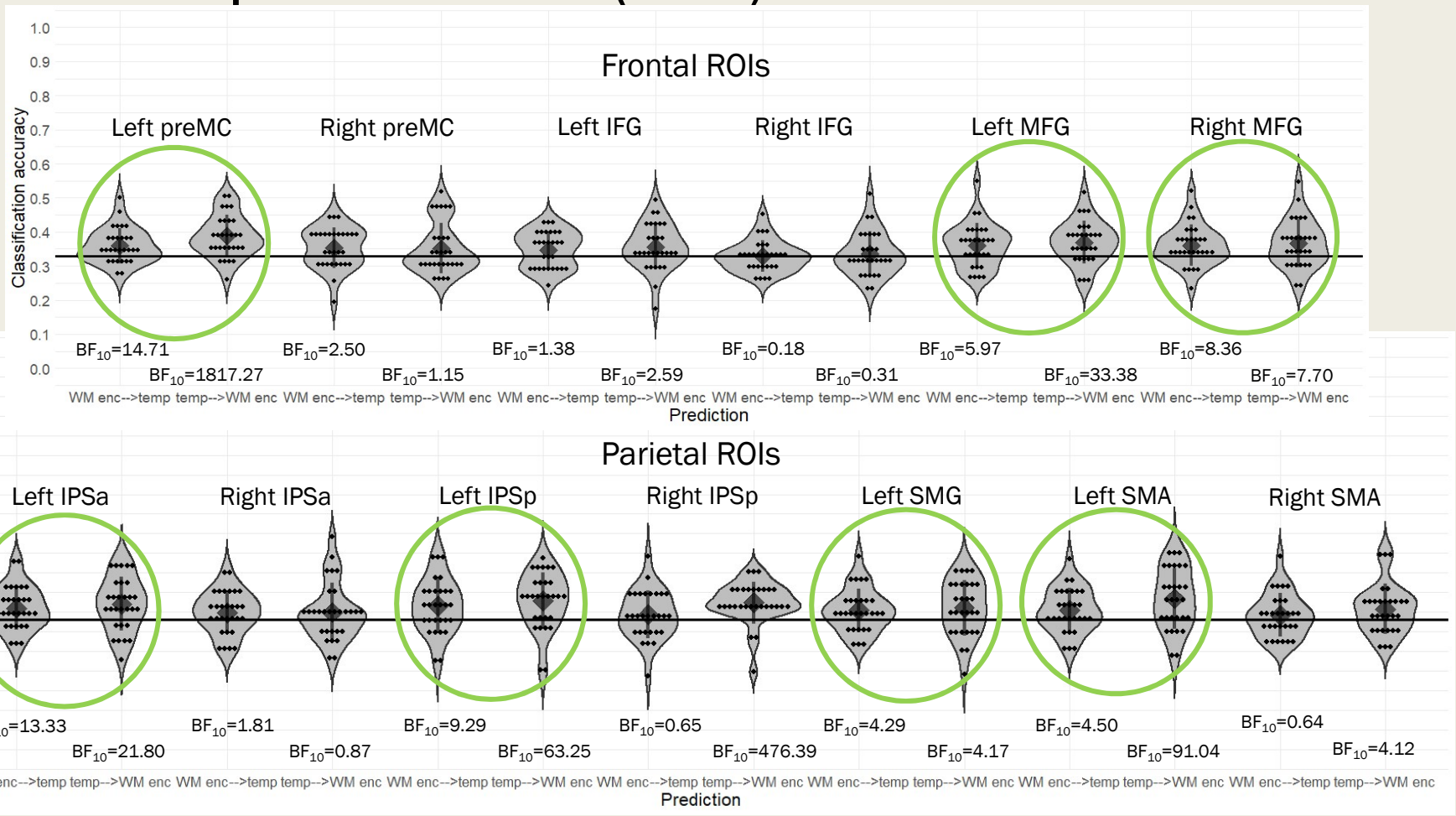
BF_{10}= 33.25

BF_{10}= 154.15

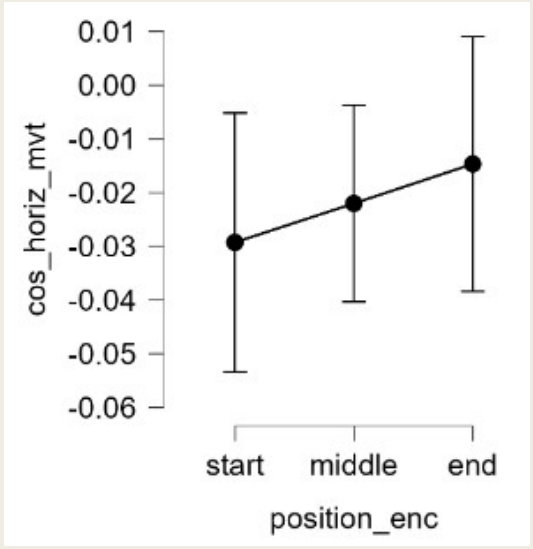
BF_{10}= 0.14

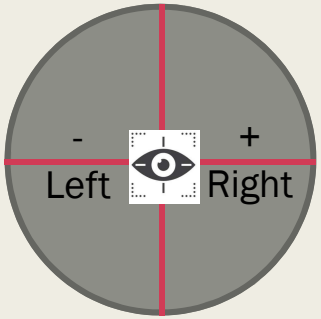
BF_{10}= 0.21

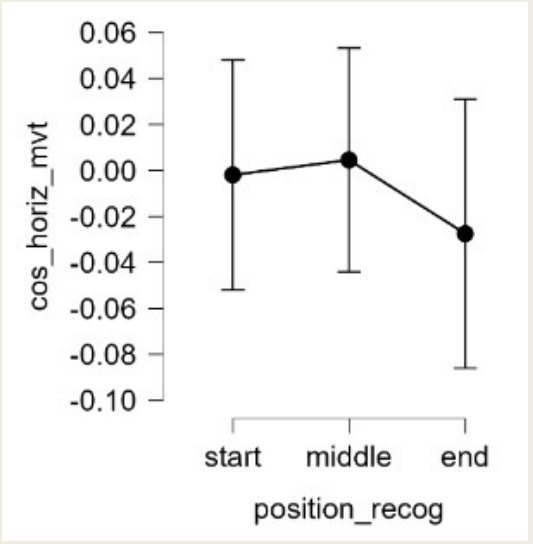
fMRI Results : classification inter-task
ROI : Temporal & WM (enc)



Eye-tracking data : serial order WM







Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Null model (incl. subject)	0.500	0.835	5.053	1.000	
position_enc	0.500	0.165	0.198	0.198	0.609

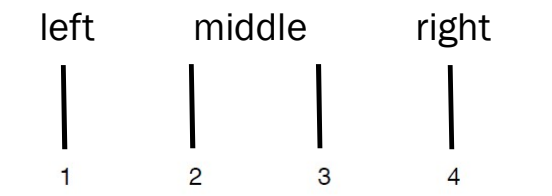
Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Null model (incl. subject)	0.500	0.828	4.828	1.000	
position_recog	0.500	0.172	0.207	0.207	0.618

Role of spatial or temporal representation in order WM

Positional models

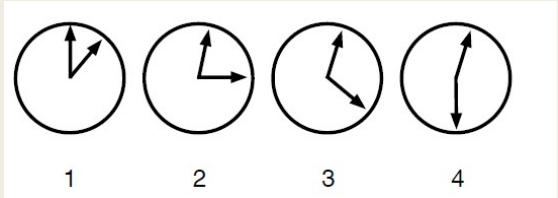
Spatial codes

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



Temporal codes

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



Discussion

- Support **several data & several models** showing the importance of the temporal dimension to code serial order in WM (Brown et al., 2000; Henson et al., 2003; Plancher et al., 2018; Fanuel et al., 2018; Gilbert, Hitch, & Hartley, 2016; Saito, 2001; De Belder et al., 2017; Hartley et al., 2016).

  - ***the left IPS*** → *as a part involved in a more general sequential order processing, including WM and alphabetical processing* *(Attout et al., 2021 Attout et al., 2014; Fias et al., 2007).*

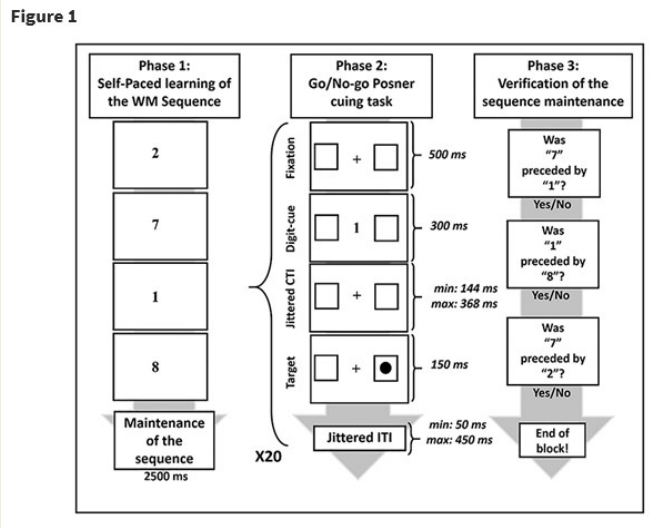
    → *involved in duration estimation in time tasks* *(e.g. Pouthas et al., 2005; Rao et al., 2001; Dormal et al., 2010; 2012; Ustun et al., 2017; see Sokolowski et al., 2017 for a review).*
  - ***MFG*** → *core part of the dorsal attentional network (Kurt et al., 2016); explicit processing of order information* *(Attout et al. 2015; 2021);* *associated with the manipulation and monitoring of multiple stimuli* *(Champod and Petrides 2010).*
  - ***Left PreMC*** → *play a role in external sensory-guided actions; link between magnitude and actions* *(Skagerlund et al., 2016).*
  - ***SMA*** → *accumulation and integration of elements into higher-order sequences + timing* *(see for a Review, Cona & Semenza, 2017)*
  - ***Left SMG*** → *amodal serial order WM (Guidali et al., xxx)*
- The specific commonality with the **encoding phase** rather than the recognition phase of the serial order WM task : Temporal markers are used as an internal coding rather than a more strategic way to code serial order in WM ?
- Temporal codes more “automatic”, inherent to verbal language – sequential → important to reproduce these results in a further study using a simultaneous presentation
- End position++ : fewer competing neighbours than items in the middle and at the start of the list ?

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

Discussion

Why the spatial attention task did not predict the serial order WM?

- Spatial codes more for the serial order LTM processes
- Spatialization is flexible → more like a strategy than a coding per se



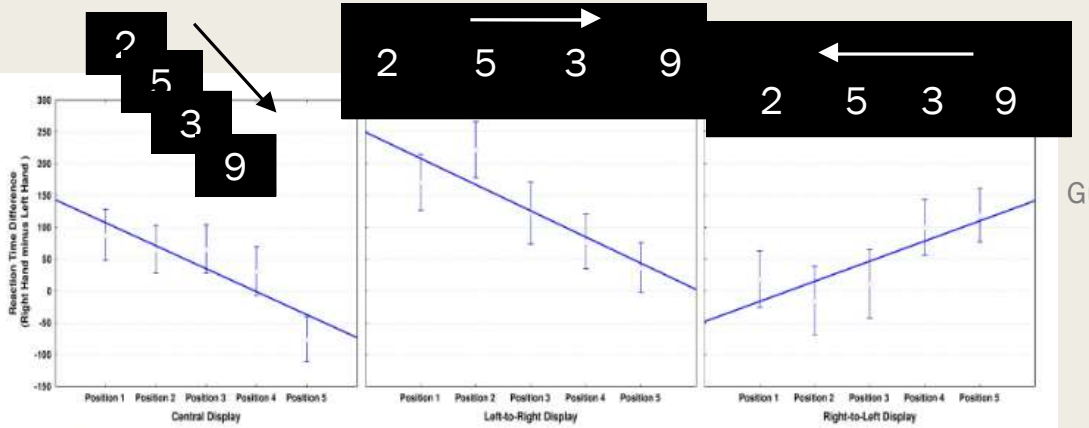


Figure 2. Observed data and regression line representing right-hand reaction times minus left-hand reaction times as a function of *position in the sequence* that was probed (five positions) and *items presentation*.

Guida et al., 2020

Conclusions

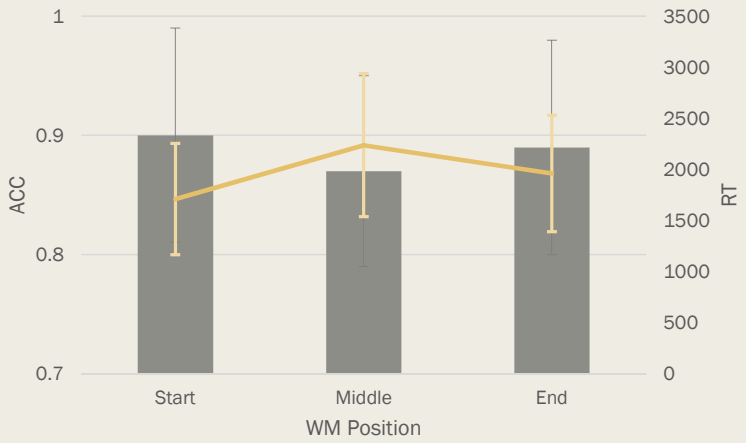
- Serial order WM required **temporal coding** but not a common representation for the three domains (Walsh, 2003; 2015; Skagerlund et al., 2016).
- This **temporal coding** engrained in the left IPS, the left preMC, the MFG, SMA and left SMG.
- However, these results are limited to the encoding phase → maybe a more (spatial) controlled processing is required to maintain (actively) and recall the information

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

THANK YOU FOR YOUR ATTENTION

Behavioral results

Bayesian repeated measures ANOVA (Positions: start-middle-end)

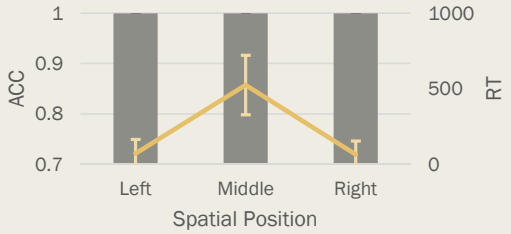


WM:

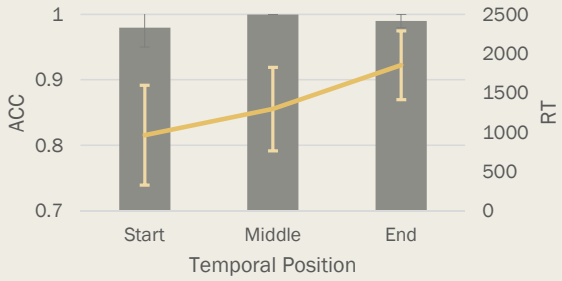
ACC: anecdotal evidence in favour of the positional effect (BF_{10}=0.38)

RT: decisive evidence for a positional effect (BF_{10}=55754.75)

Spatial task: Faster response times for rightwards and leftwards dot stops relative to central dot stops (respectively, BF_{10}=1.96E+11 and BF_{10}=3.01E+11).



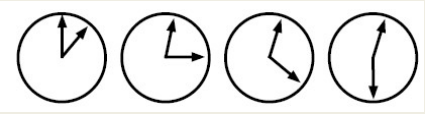
Temporal task, start position led to faster response times than the middle and the end positions (respectively, BF_{10}=3.58E+6 and BF_{10}=2.17E+15), relative to the trial onset.



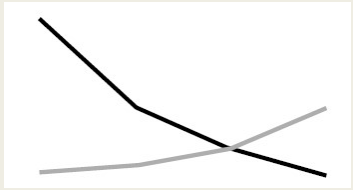
Serial order WM models

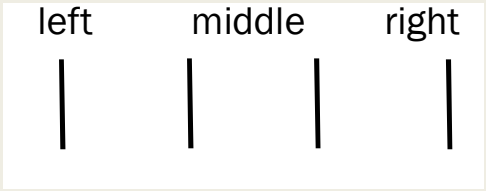
Positionnal models

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

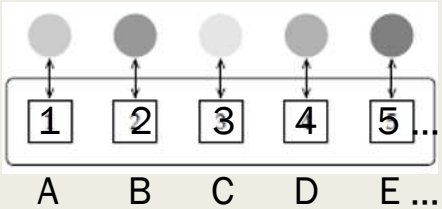


Spatial markers
(Start-end, Henson, 1998; Abrahamse et al., 2014; Van Dijck et al., xxx; Guida et al., xxx)



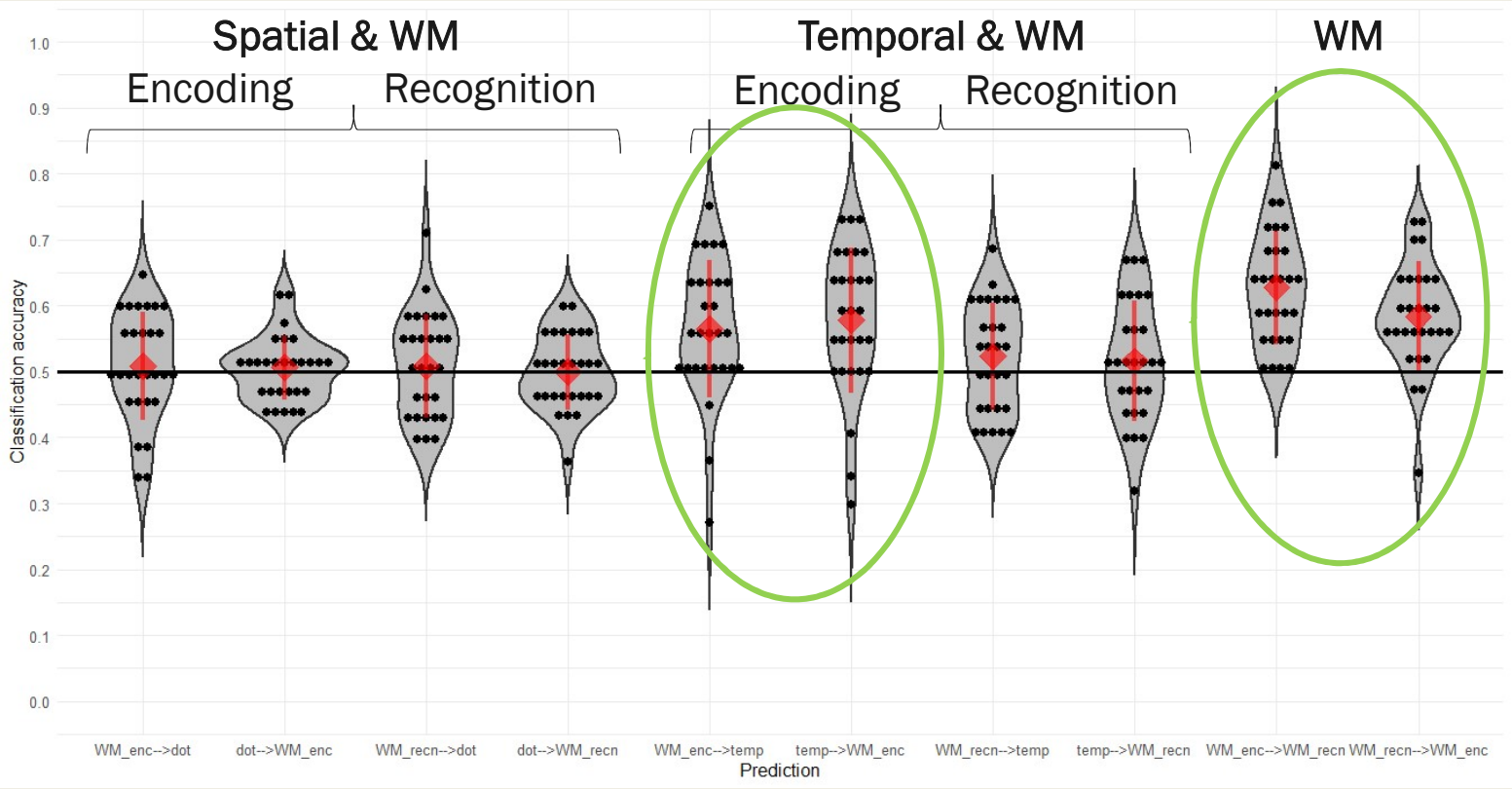


Rank markers
(Botvinick & Watanabe, 2007; Attout et al., 2014; 2021 Majerus & Oberauer, xxx)



Prediction between start vs. end : WB

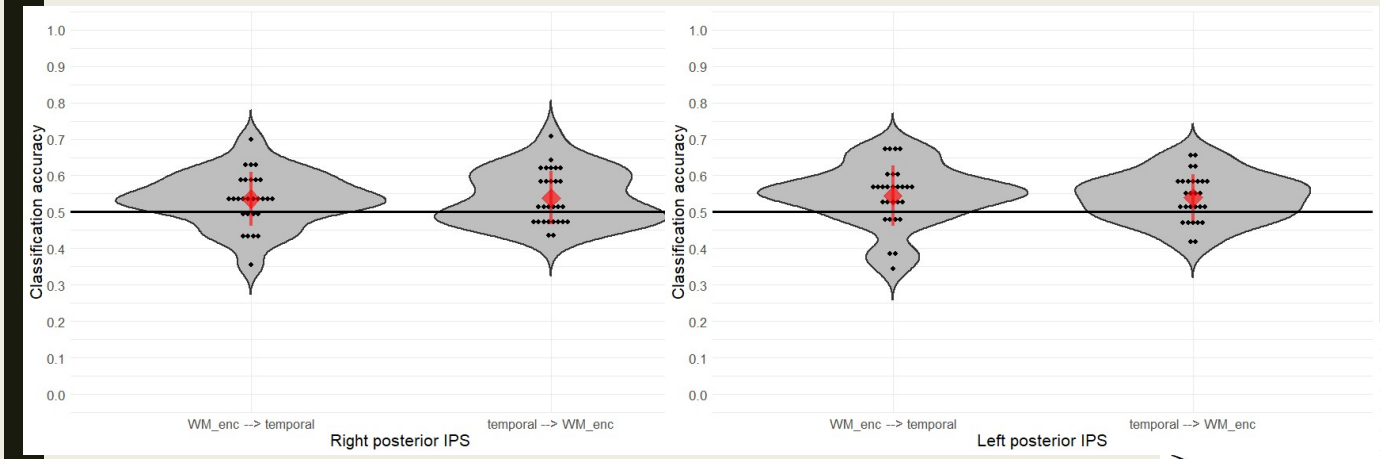
Prediction between spatial/temporal tasks & the WM task (for encoding and recognition) for the classification between start-of-list/left VS end-of-list/right

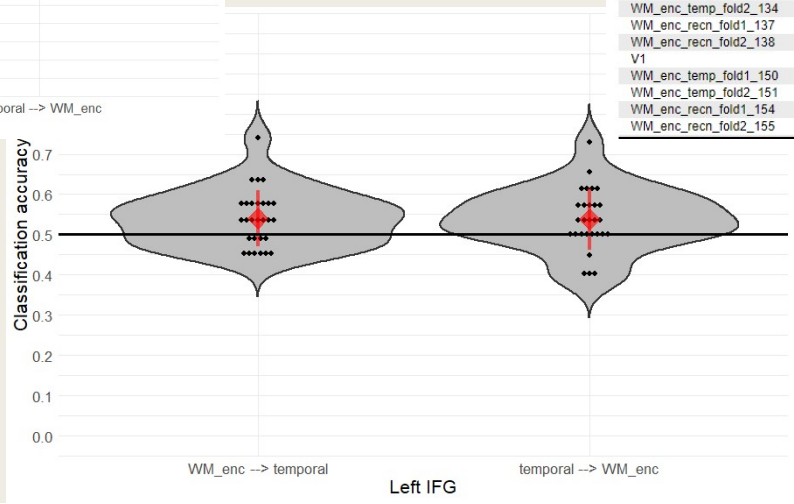


Bayesian One Sample T-Test	
	BF_{∞}
dot_temp_fold1_37	0.217
dot_temp_fold2_38	0.361
WM_enc_dot_fold1_39	0.317
WM_enc_dot_fold2_40	0.358
WM_recn_dot_fold1_41	0.332
WM_recn_dot_fold2_42	0.191
WM_enc_temp_fold1_43	25.890
WM_enc_temp_fold2_44	76.568
WM_recn_temp_fold1_45	1.009
WM_recn_temp_fold2_46	0.478
WM_enc_recn_fold1_47	1.381e +6
WM_enc_recn_fold2_48	3957.313

Prediction between start vs. end : ROI

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





Bayesian One Sample T-Test

	BF_{∞}
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

Memory benefited from temporal regularities

- When implemented at **encoding**

Povel & Essens, 1985 ; Silverman & Schwartzberg, 2014 ; Tillmann & Dowling, 2007

- **B**ottom-**U**p **M**ulti-scale **P**opulation oscillators model

Hartley, Hurlstone & Hitch, 2016

Order WM – Nature of representation

Spatial codes

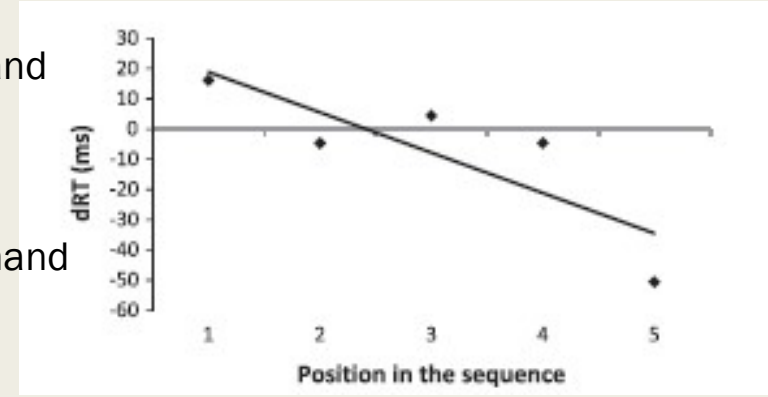
Phase 1
Maintenance
3-7-1-4-9

Phase 2 : Go/no go task:
Parity judgment task
2? 3? 8? 9?

Phase 3
Recall

Left hand

Right hand



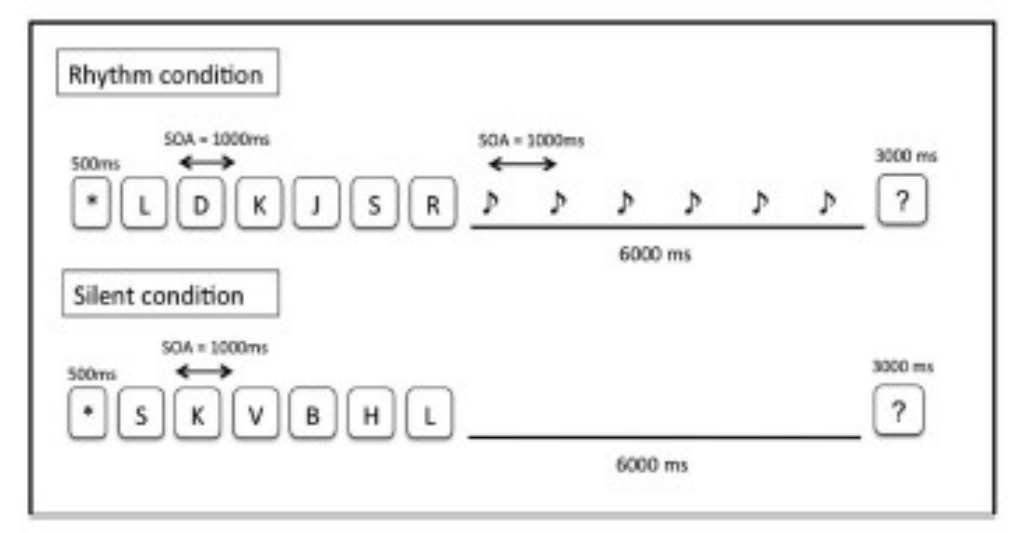
interaction between serial order retrieval from verbal WM and spatially defined response options

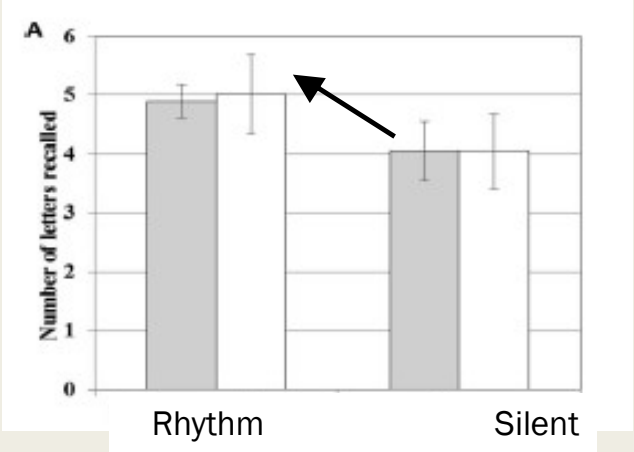
Van Dijck & Fias, 2011

Order WM – Nature of representation

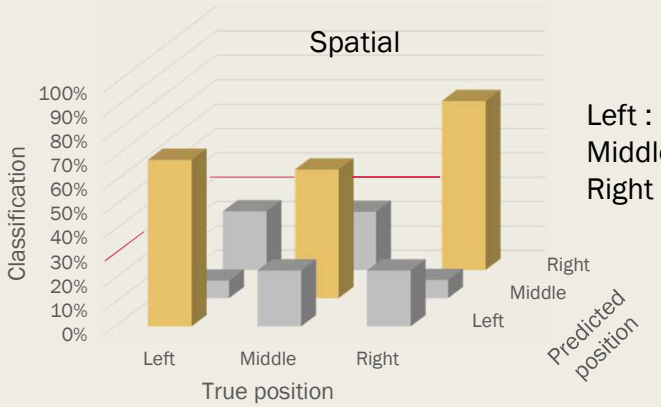
Temporal codes

Plancher et al., 2017; Henson et al., 2003

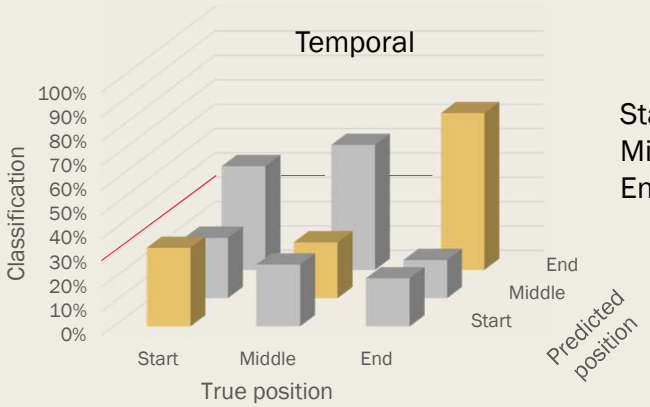




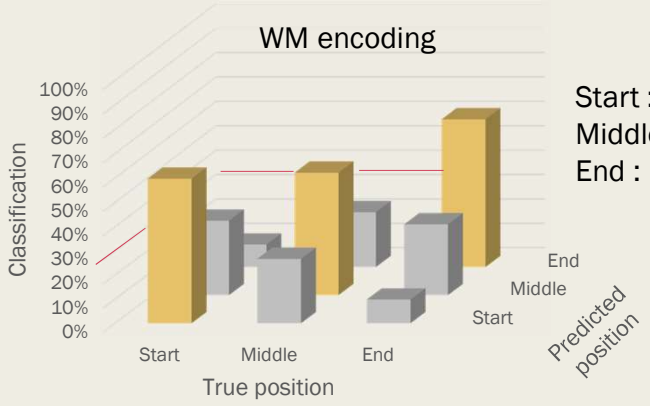
fMRI Results : classification intra-task Whole-brain



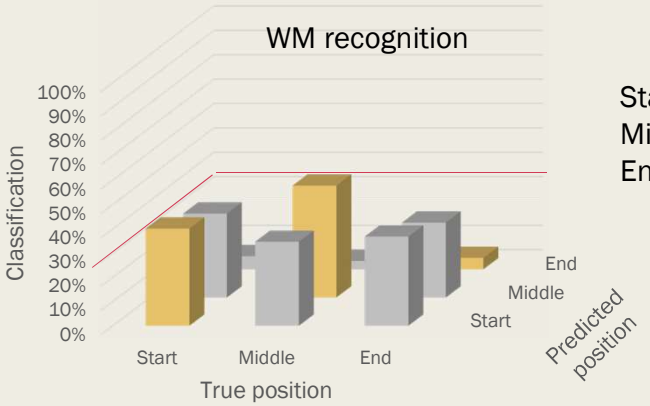
Left : BF_{10}= 1.16^{E}+15
Middle : BF_{10}= 1.52^{E}+4
Right : BF_{10}=4.12^{E}+14



Start: BF_{10}= 0.17
Middle : BF_{10}= 0.06
End : BF_{10}= 2.12^{E}+6



Start : BF_{10}= 1.92^{E}+9
Middle : BF_{10}= 4.24^{E}+8
End : BF_{10}= 1.42^{E}10



Start : BF_{10}= 0.83
Middle : BF_{10}= 9.47
End : BF_{10}=0.17

fMRI Results : classification inter-task
Whole-brain : temporal_WM_enc

	BF_{-0}	error %
WM_enc_temp1_fold1	0.403	~ 2.083e−6
WM_enc_temp1_fold2	0.158	~ 1.695e−4
WM_enc_temp2_fold1	0.122	~ 0.002
WM_enc_temp2_fold2	0.103	~ 9.845e−4
WM_enc_temp3_fold1	56.683	~ 5.098e−4
WM_enc_temp3_fold2	11385.660	NaN[a]

MVPA analyses

Within : Leave-one-block-out (LOBO) cross-validation procedure

Between : Leave-one-run-out (LORO) cross-validation procedure