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Study Rationale

- Contextual Control: People must consider context to determine how to seek their goals in a complex world. The same cue may inform different behavior depending on the situation¹
 - An increase in contextual control was associated with delta (2-3 Hz) oscillations, whereas theta (4-7 Hz) oscillations were observed when the control demand (number of contexts/rules) increased^{2,3,4}
 - Low frequency prefrontal activity is also involved in rule processing^{5,6}
- The frontal cortex is hierarchically organized along the rostral-caudal axis, from motor execution in caudal areas to planning and decision-making in rostral regions^{1,7,8}
 - The mid-dorsal lateral prefrontal cortex (mid-dIPFC) integrates abstract and concrete representations to regulate behavior

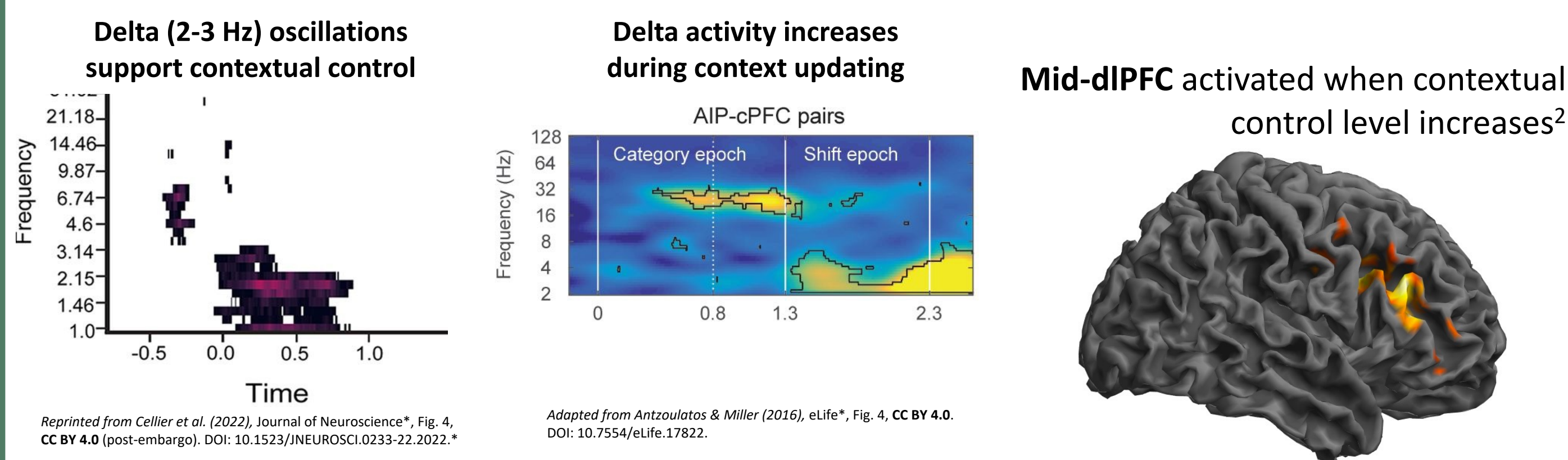
What we did

- We applied rhythmic Transcranial Magnetic Stimulation (rTMS) during a Hierarchical Cognitive Control Task which engages both stimulus-response mappings and higher-level contextual cues. We also manipulate the number of active rules, introducing competition demand and requiring flexible rule selection
 - Participants received rhythmic TMS to mid-dIPFC and PMd at delta (2.2 Hz) or theta (6.5 Hz) frequencies; for each frequency, we included a matched arrhythmic control
- We aim to causally test whether delta TMS in lateral PFC support abstract rule processing.
- We hypothesized that delta TMS to mid-dIPFC would improve contextual control (better performance in higher contextual control task conditions) and may facilitate context updating

What we found

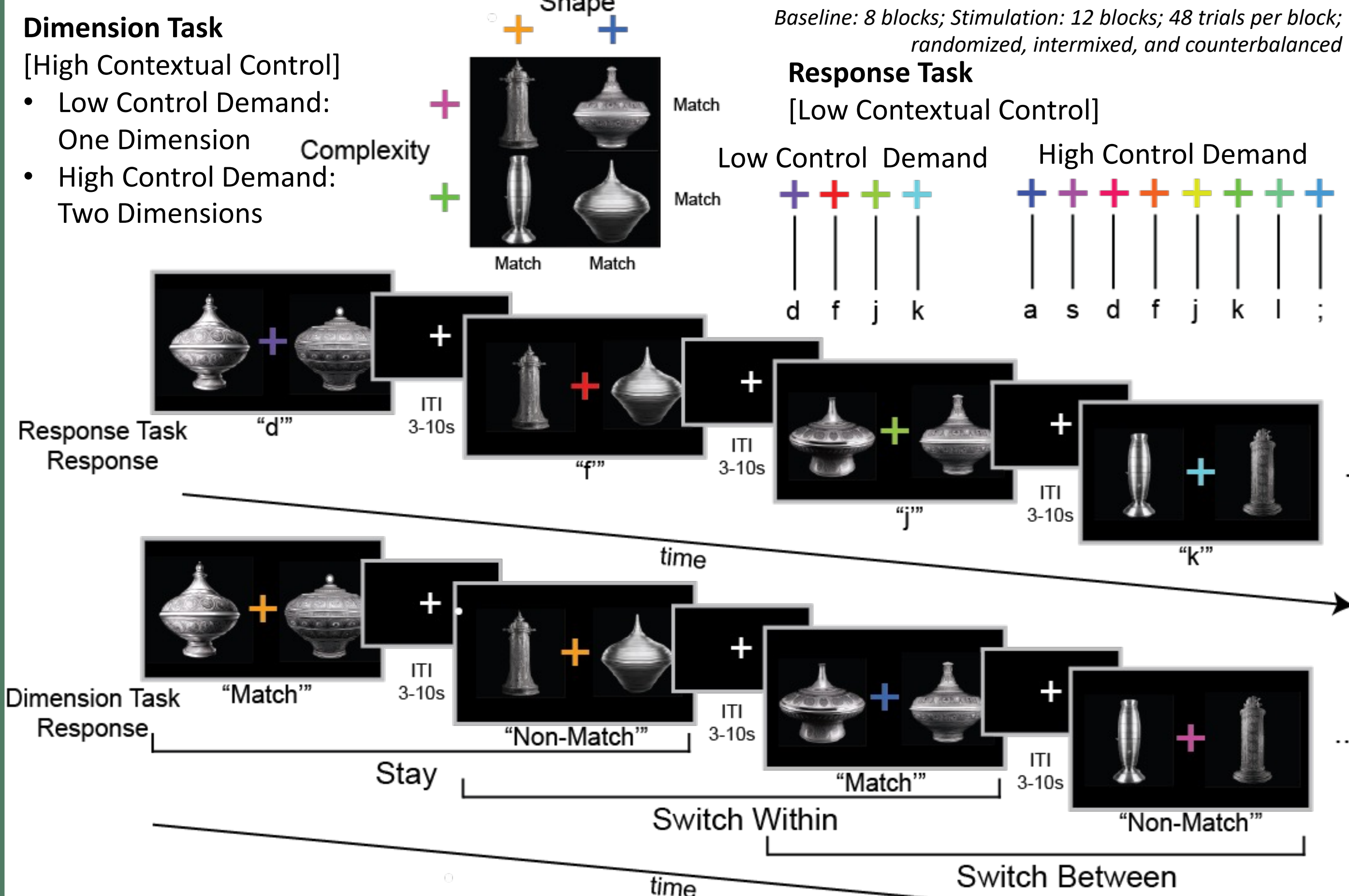
- Frequency-specific stimulation of mid-dIPFC modulated contextual control performance ($Freq \times CC, p = .020$), indicating a causal role of low-frequency oscillations in higher-order control processes.
- No comparable effects were observed in PMd, supporting regional specificity of oscillatory modulation and dissociating prefrontal control from motor-related processing.
- Stimulation effects were selective to contextual control, with no significant interactions involving general task demand, suggesting targeted modulation rather than global performance enhancement.
- Accuracy remained unaffected across conditions, indicating that TMS influenced processing efficiency (reaction time) without compromising task performance.

Theoretical Motivation



- Task-relevant rule representations are expressed in low-frequency band⁵
- Fronto-parietal connectivity in the delta band increases during a shift in task rule⁶

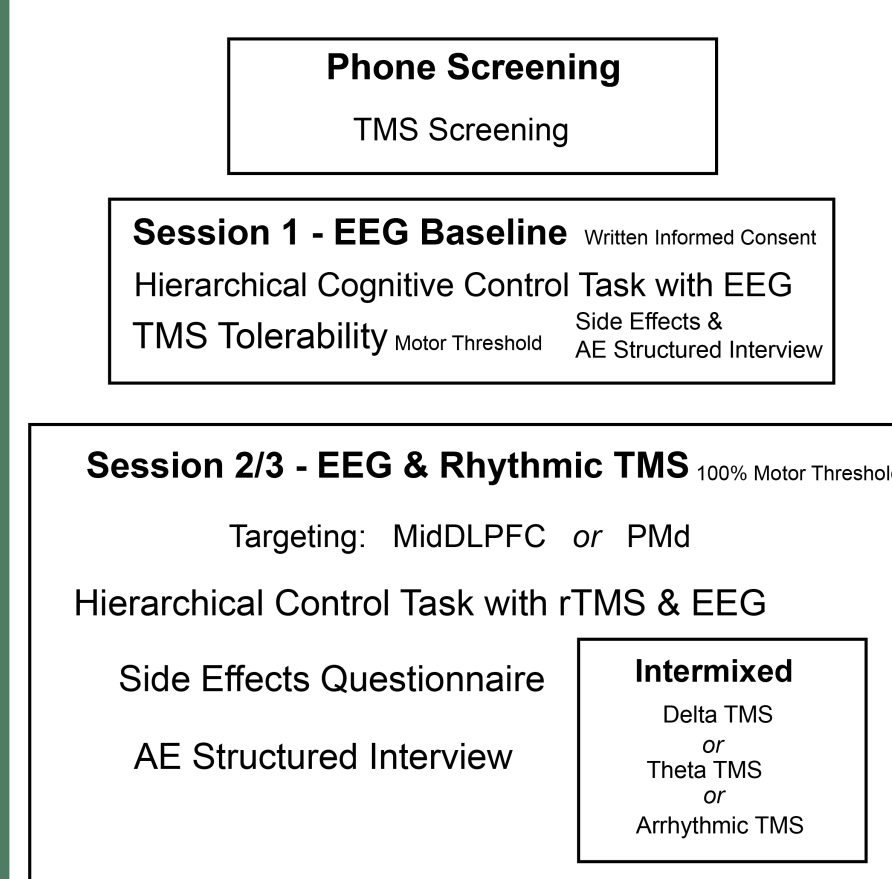
Hierarchical Cognitive Control Task



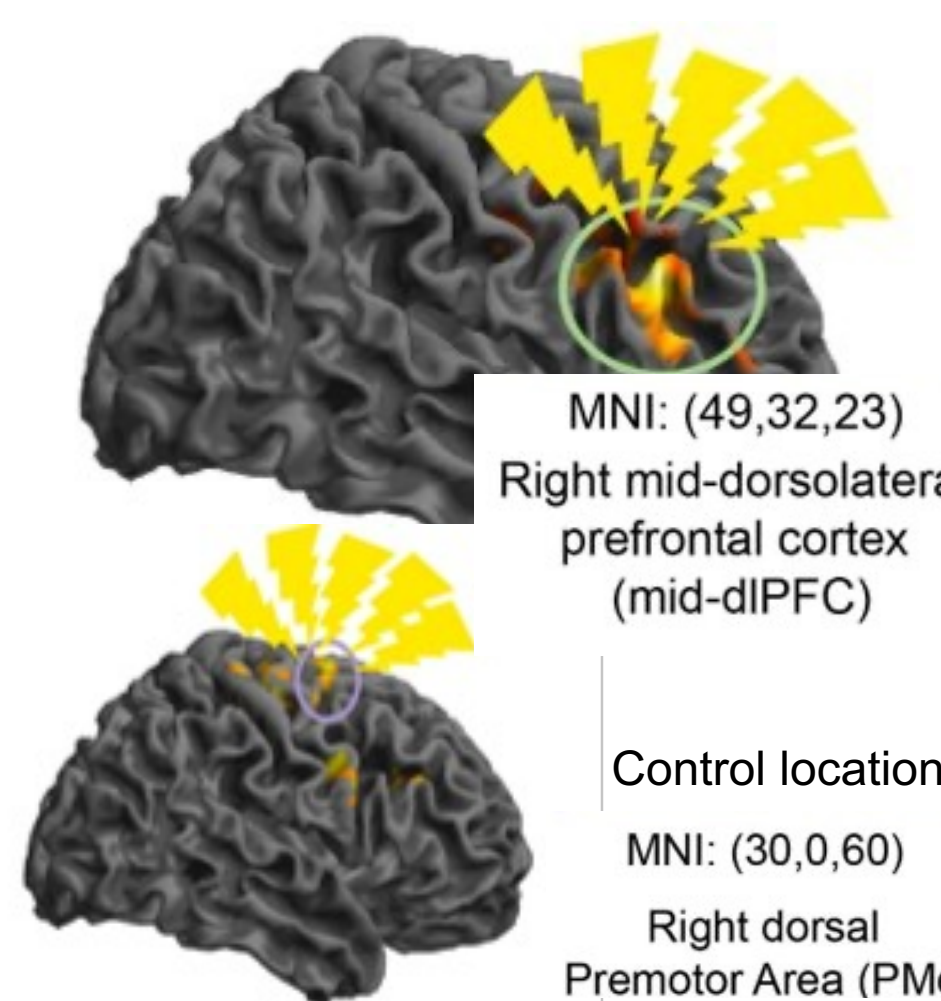
Experimental Design

- This analysis was run on 66 participants for baseline session and 48 for completed three session (35 female; M = 21.0 years, SD = 3.4)

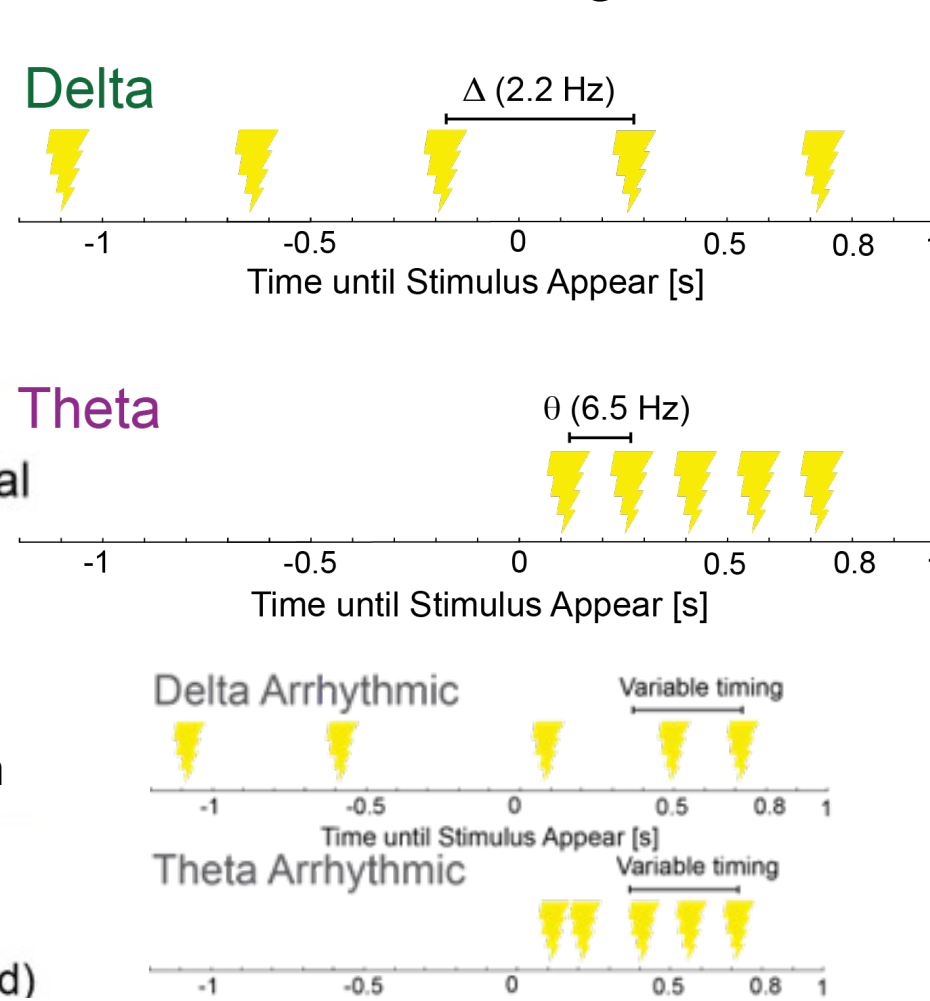
Experimental Schema



TMS Location



TMS Timing



Baseline Behavior

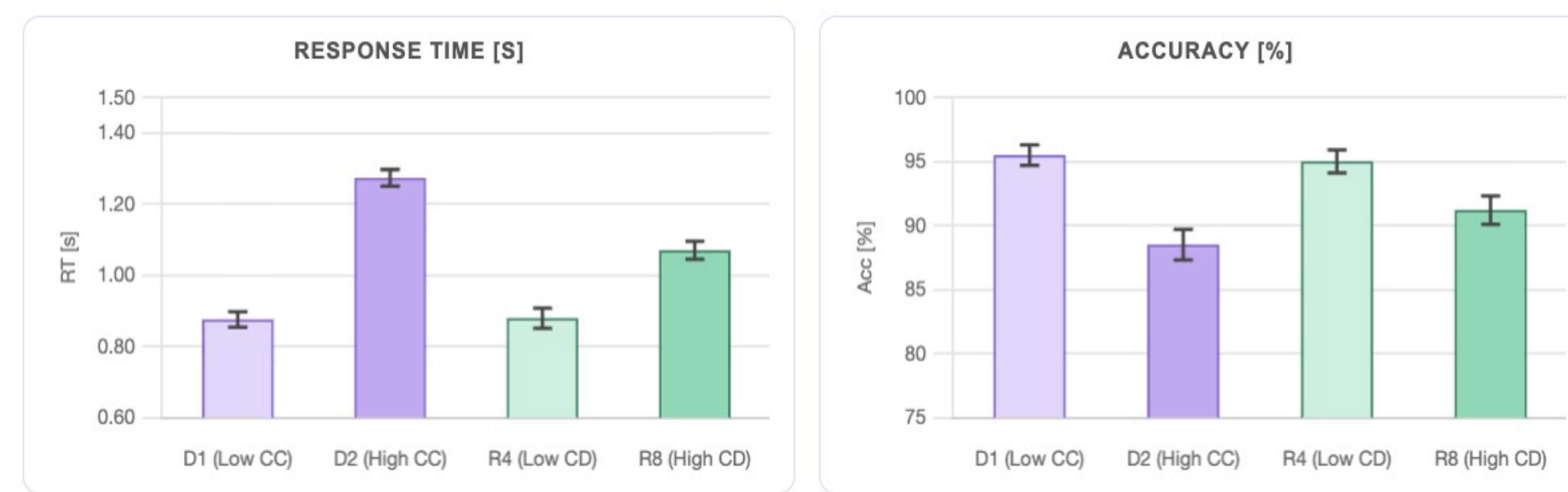
Contextual Control

Two-way repeated-measures ANOVA with factors Contextual Control (high & low) and Control Demand (high & low) for response time on all participants

ANOVA	df	F	p	η_p^2
Contextual Control	1,65	67.32	<0.001***	0.51
Control Demand	1,65	932.6	<0.001***	0.94
CC × Demand	1,65	164.5	<0.001***	0.72

Two-way repeated-measures ANOVA with factors Contextual Control (high & low) and Control Demand (high & low) for accuracy on all participants

ANOVA	df	F	p	η_p^2
Contextual Control	1,65	11.03	0.001***	0.15
Control Demand	1,65	43.77	<0.001***	0.40
CC × Demand	1,65	2.30	0.134	0.03



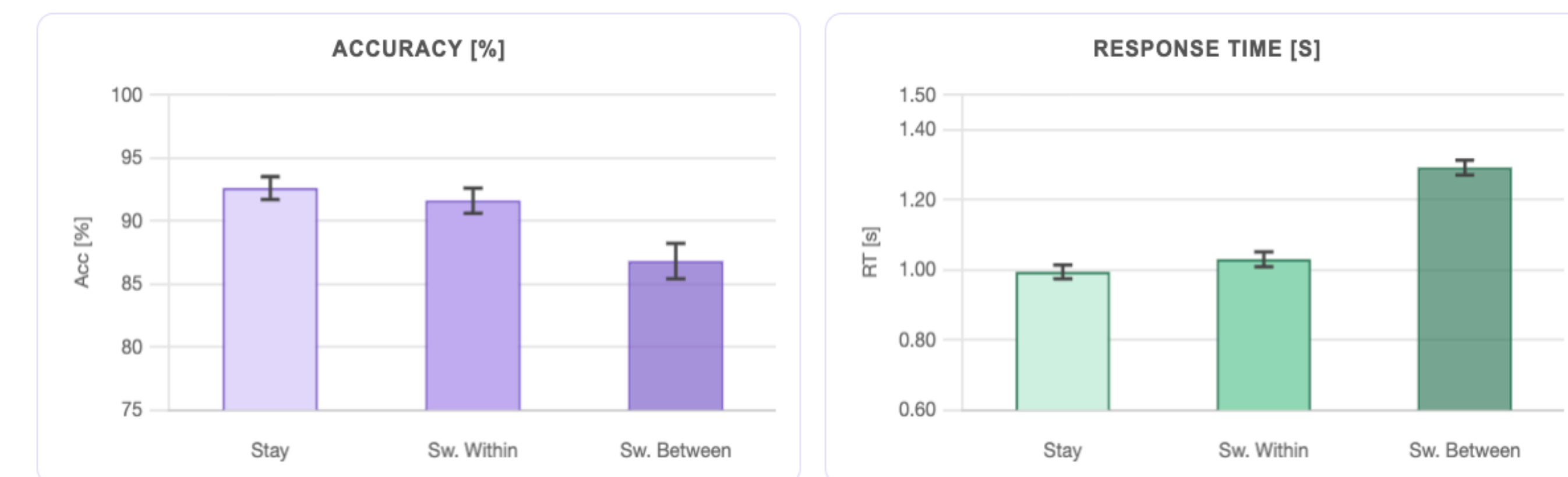
Context Update

Repeated-measures ANOVA with factors context updating condition (stay, switch within, switch between) for response time on all participants

ANOVA	df	F	p	η_p^2
Updating Condition	2,130	421.9	<0.001***	0.866

Repeated-measures ANOVA for accuracy on all participants

ANOVA	df	F	p	η_p^2
Updating Condition	2,130	20.10	<0.001***	0.236



- The task successfully manipulates contextual control and control demand
 - For context update conditions, accuracy only did not differ between within-dimension and between-dimension context switches (n.s.)
- * p < 0.05; ** p < 0.01; *** p < 0.001. Error bars are within-participant SEM

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TMS Behavior

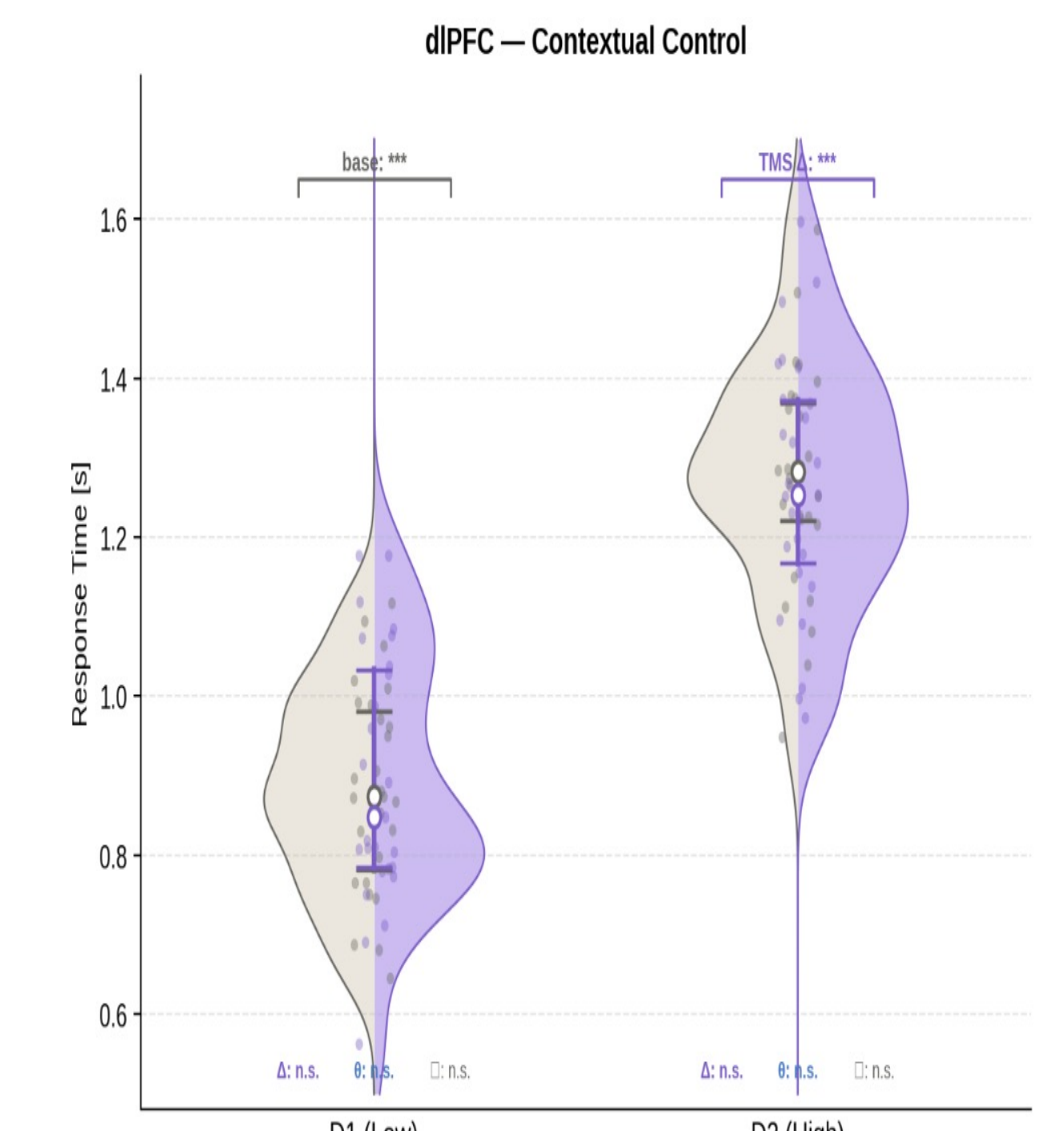
Contextual Control

Three-way repeated-measures ANOVA with factors Contextual Control (high & low), Control Demand (high & low), and TMS frequency (delta, theta, arrhythmic) for response time — TMS to mid-dIPFC

ANOVA	Df	F	p	η_p^2
Freq × CC	2,94	4.10	0.020*	0.07
Freq × Demand	2,94	2.22	0.114	0.05
Freq × Demand × CC	2,94	1.37	0.258	0.00

Three-way ANOVA for response time — TMS to PMd

ANOVA	df	F	p	η_p^2
Freq × CC	2,94	1.04	0.357	0.00
Freq × Demand	2,94	0.37	0.689	0.00
Freq × Demand × CC	2,94	1.60	0.207	0.05



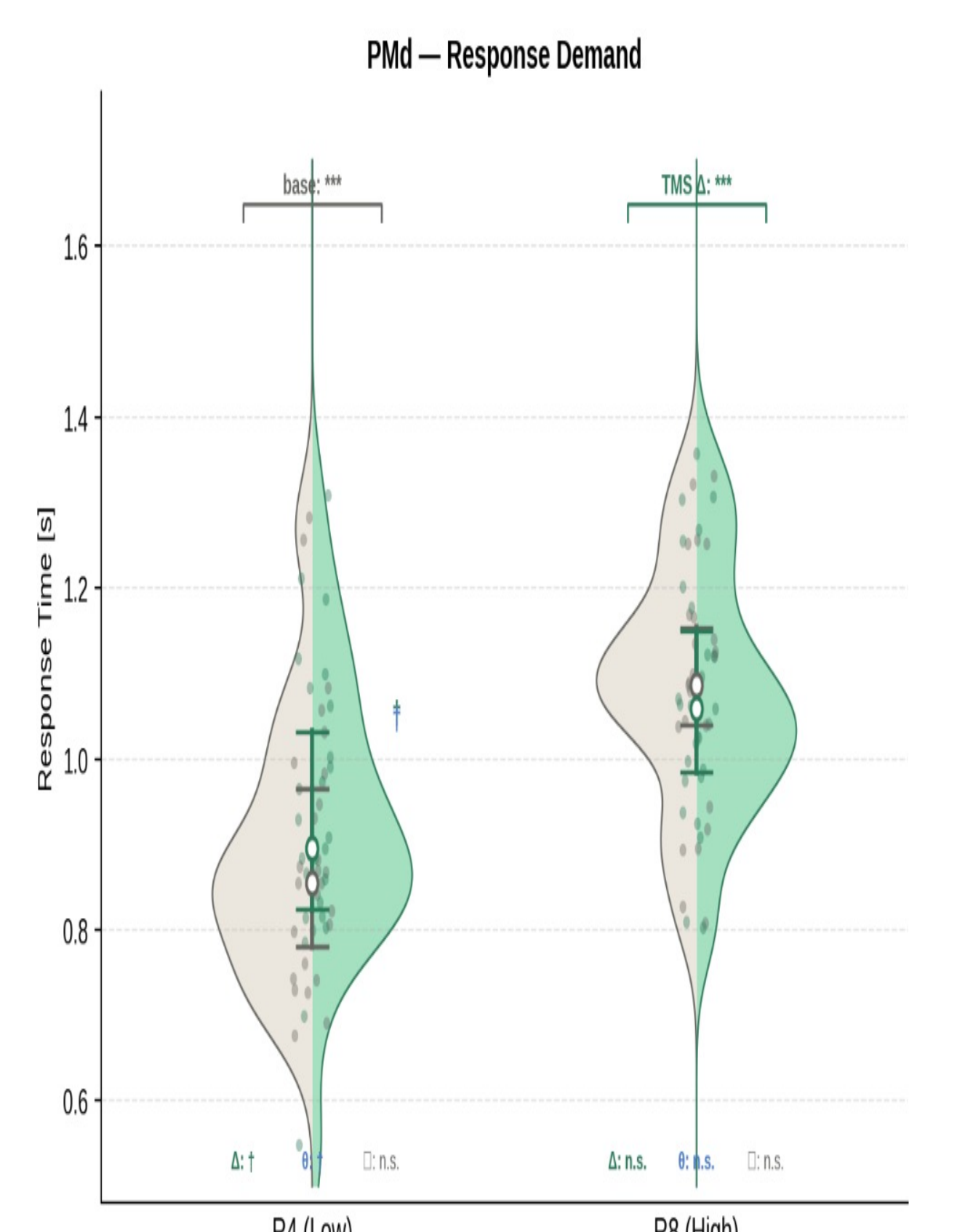
Context Update

Three-way repeated-measures ANOVA with factors context updating condition (stay, switch within, switch between), stimulation location (PMd, mid-dIPFC) and TMS frequency for response time on all participants

ANOVA	df	F	p	η_p^2
Freq × Site	2,94	0.04	0.964	0.00
Freq × Updating	4,188	2.08	0.085†	0.04
Site × Updating	2,94	0.94	0.395	0.00
Freq × Site × Updating	4,188	0.24	0.917	0.00

Three-way ANOVA for accuracy on all participants

ANOVA	df	F	p	η_p^2
Freq × Site	2,94	0.35	0.703	0.01
Freq × Updating	4,188	0.42	0.797	0.01
Site × Updating	2,94	2.52	0.086†	0.01
Freq × Site × Updating	4,188	0.30	0.875	0.01



Future Direction

- We plan to collect structural and functional neuroimaging data to determine functional connectivity patterns associated with hierarchical cognitive control and if personalized stimulation based on T1 imaging can enhance behavioral and neural effects
- Additionally, we plan to analyze the high-density EEG data using time-frequency analyses to discern whether the TMS entrained delta prefrontal oscillations

Acknowledgement

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