Two dominant brain states reflect optimal and suboptimal attention

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INTRODUCTION

- Finding brain markers of optimal attentional state is important
- Two limitations of defining attention states based on performance in the previous study

1. **Require continuous performance**
   - Constraining the types of tasks
2. **Low dimensionality of behavioral performances**
   - Resulting in blunt methods like dichotomization

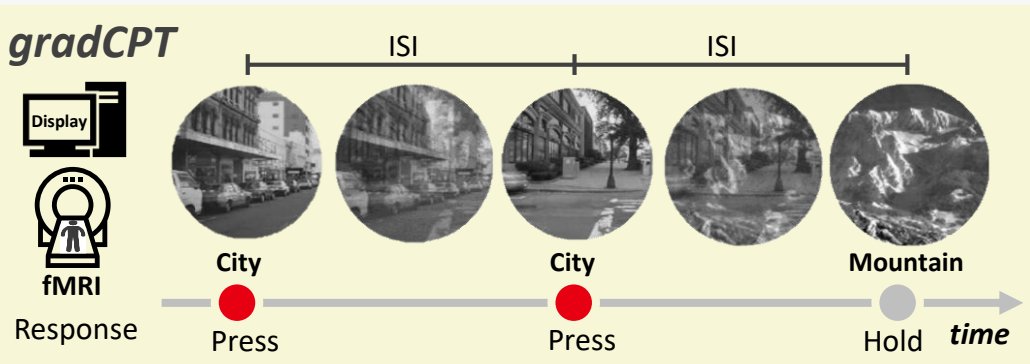
Research questions

1. Can attentional fluctuation be detected by brain activity alone agnostic to behavioral performance?
2. How are these states impacted by motivation, mind wandering, and attention-deficit hyperactivity disorder (ADHD).

MATERIALS & METHODS

Behavioral performances

(Gradual onset continuous performance task: gradCPT [1])



- Images gradually change
- Press for city image
- Hold for mountain image

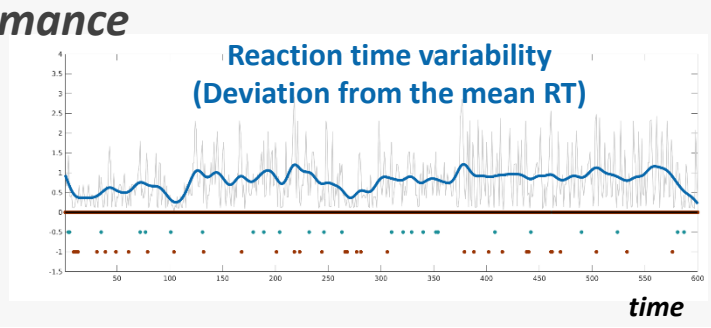
- 90% city and 10% mountain
- ISI: 800 ms or 1300 ms
- Time: 8 - 9 min

Data set
- 61 healthy participants
- 19 ADHD patients

Behavioral performance

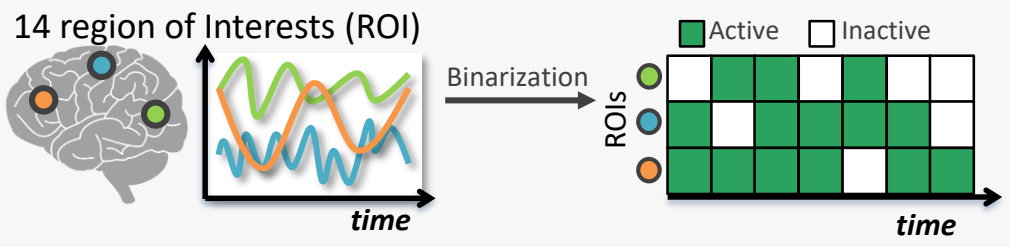
Press mountain
Hold mountain
Hold city
Press city

→ Accuracy (d prime)



How to define brain state (Energy landscape analysis [2])

(1) Extract BOLD signals (fMRI preprocessing: *fmriprep* [3])



(2) Calculate energy of each brain activity pattern (Energy landscape)

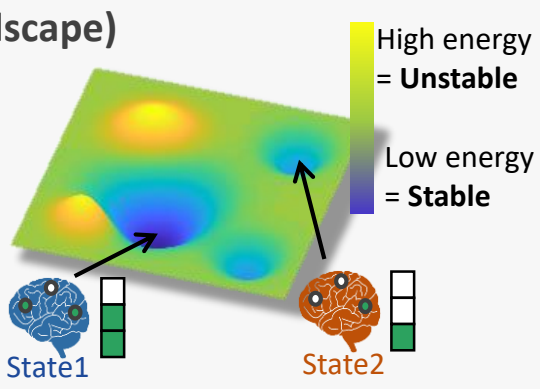
Probability

$$P(\boldsymbol{\sigma}|\boldsymbol{h},\boldsymbol{j}) = \frac{\exp[-E(\boldsymbol{\sigma}|\boldsymbol{h},\boldsymbol{j})]}{\sum_{\boldsymbol{\sigma}'}\exp[-E(\boldsymbol{\sigma}'|\boldsymbol{h},\boldsymbol{j})]}$$

Energy

$$E(\boldsymbol{\sigma}|\boldsymbol{h},\boldsymbol{j}) = -\sum_{i=1}^{N} h_i\sigma_i - \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N} J_{i,j}\sigma_i\sigma_j$$

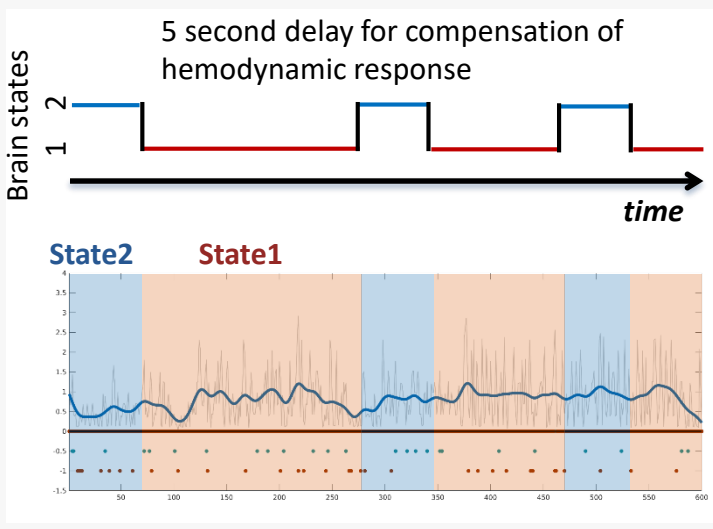
$\boldsymbol{\sigma}$: Activity pattern, $\boldsymbol{h}$: Mean activation
$\boldsymbol{j}$: Brain connectivity



Relationship between brain state and behaviors

Brain state transition

Behavioral performance



Investigation of the influence of additional cognitive factors

Mind wandering [4]

- Mind wandering was measured by thought probe

High mind wandering block
- High mind wandering time within session (above median)

Low mind wandering block
- Low mind wandering time within session (below median)

Motivation (reward) [5]

- Motivation was modulated by reward

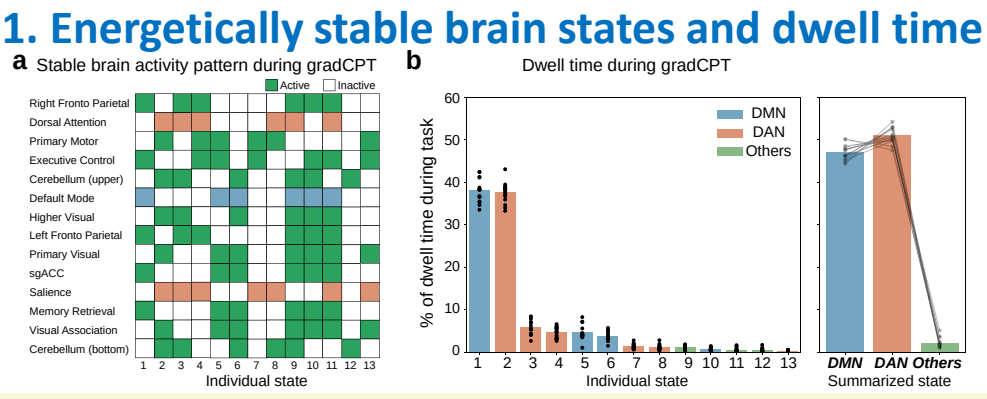
Motivated block
- Earned $0.01 or $0.10 for correct response and lose $0.01 or $0.10 for miss response.

Un-motivated block
- No money could be gained or lost.

Conducted energy landscape analysis for each block separately, and investigate the difference.

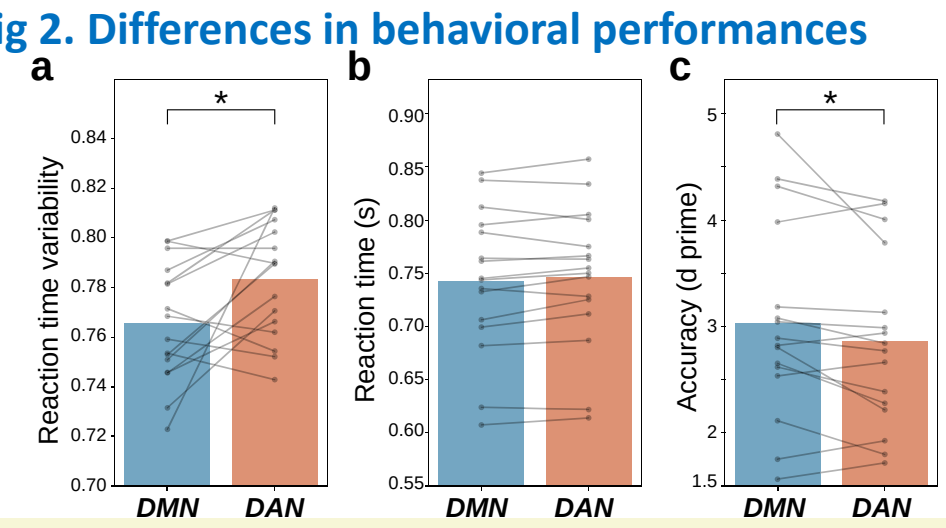
RESULTS

Fig 1. Energetically stable brain states and dwell time



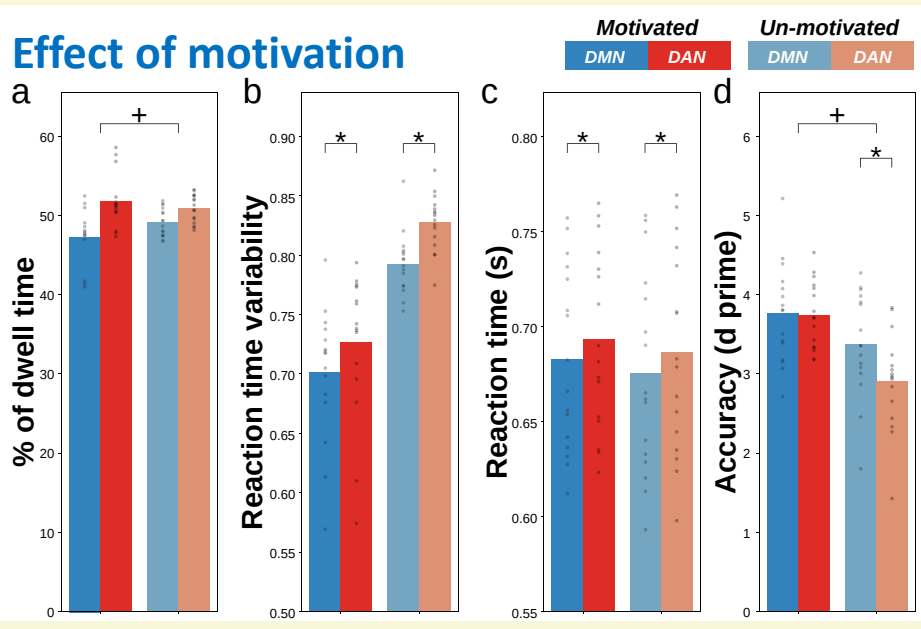
(a) Stable brain activity patterns. **(b)** The percentage of dwell time. Individual brain states were divided into two major brain states (DMN-state and DAN-state). **DMN-state and DAN-state could cover 48 % and 51% of total time, respectively.** Statistical analysis: DMN: Default mode network, DAN: Dorsal attention network

Fig 2. Differences in behavioral performances



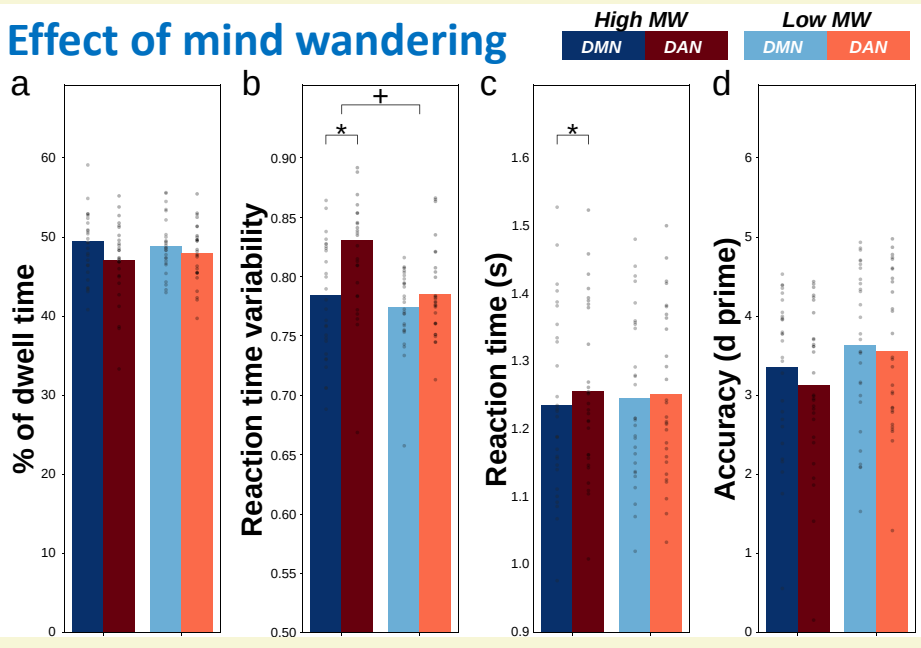
- Reaction time variability and d prime were significantly better in DMN-state, Wilcoxon signed-rank test, *$p < 0.05$

Fig 3. Effect of motivation



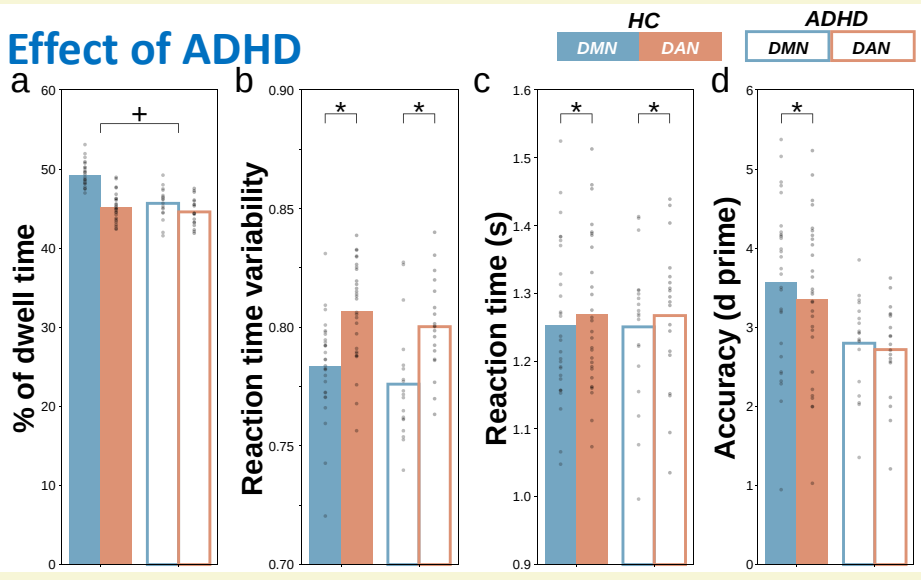
- Interaction effect was significant in accuracy.
- Motivation partially overcomes the negative effect of the suboptimal DAN-state.

Fig 4. Effect of mind wandering



- Interaction effect was significant in reaction time variability.
- Mind wandering worsen the negative effect of the suboptimal DAN-state.

Fig 5. Effect of ADHD



- Interaction effect was significant in dwell time.
- Individuals with ADHD spent less time in the optimal DMN-state.

Statistical analysis: Mixed effects model, +: interaction effect ($p < 0.05$), *: main effect ($p < 0.05$), two-sided without multiple comparisons

CONCLUSION

- We found the two dominant brain state such as an optimal DMN-state and a suboptimal DAN-state
- Motivation partially overcomes the negative effect of the suboptimal DAN-state
- Mind wandering worsen the negative effect of the suboptimal DAN-state
- Individuals with ADHD spent less time in the optimal DMN-state than healthy controls

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