A hidden state analysis of prefrontal cortex activity underlying trial difficulty and erroneous responses in a distance discrimination task

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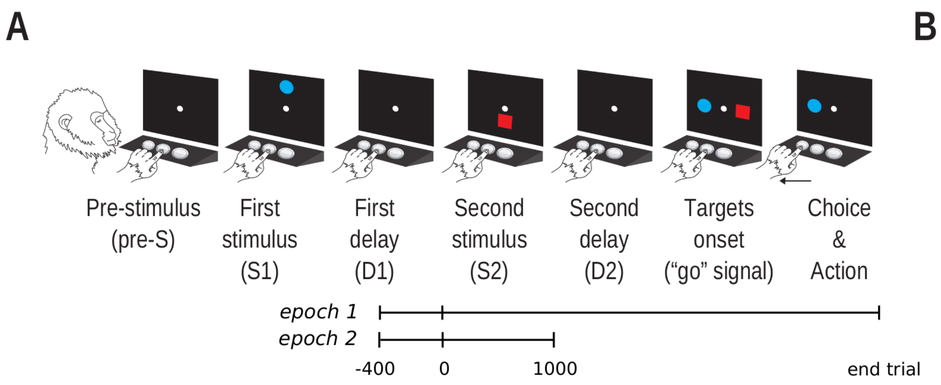
① Introduction

Prefrontal cortex (**PFC**) neurons are involved in the decision process during a **distance discrimination task** since single neurons are selective to stimulus distance and decision target [1]. However, no relationship has been found between single neurons' activity and behavioral performance or trial difficulty. Here, we analyze the neural ensemble activity with a **Hidden Markov Model** (HMM) [2, 3] and report that neural ensemble activity in dorsal PFC unfolds as a sequence of metastable states, which is modulated by task and behavioral variables (*correct rate and trial difficulty*). We found that errors are more often made when the metastable dynamics slows down, as measured by the *average duration of the metastable states* after the presentation of the second stimulus S2. Errors were not necessarily made in more difficult trials, however, and indeed there was no relation of temporal dynamics to trial difficulty. However, we found that the *first transition after S2* (fTaS2) was on average longer in more difficult trials performed correctly, while reaction times (related to movements occurring after the GO signal) were not related to either average state duration or fTaS2. These results suggest that changes in the dynamics of metastable activity in dorsal PFC underlies behavioral performance and may code for trial difficulty (see also [4]).

② Behavioral Task

Task:

- Distances of S1 and S2 above or below the reference point: $[8, 16, 24, 32, 40, 48]$ mm
- Levels of difficulty $|\Delta S| = |S1 - S2| = [8, 16, 24, 32, 40]$ mm



Research questions:

- **how do the state dynamics change between correct and incorrect trials?**
- **how is the state dynamics affected by the task difficulty in correct trials?**

③ Modeling and Data Analysis

A **Poisson Hidden Markov model** was used to study the dynamics of neural ensembles

- M hidden states, each comprising the stationary firing rates of N neurons
- for each state i, E_{ij} is the instantaneous firing probability of neuron j
- $A = A\{r, s\}$ gives the probability to move from state r to state s
- *training phase*: Baum-Welch algorithm
- *state decoding*: posterior prob ≥ 0.8 for at least 50 consecutive ms [3]
- *session selection*: $N \geq 4$, spiking activity ≥ 1 spk/s and at least 5 completed trials

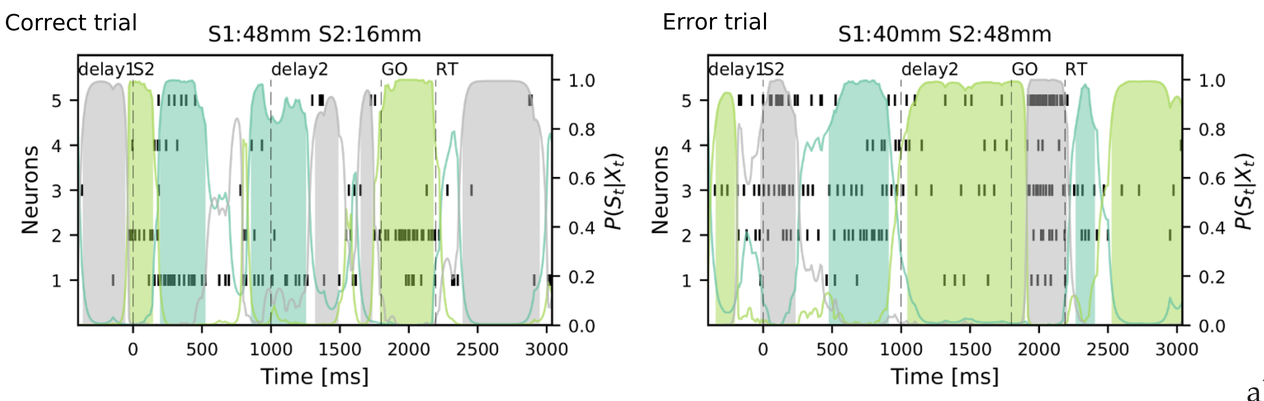
Correct vs. Incorrect trials:

- *epoch 1*: 400 ms before S2 until the end of the trial
- mean state duration in *epoch 1*
- $M = 2 \ldots N - 1$ selected by the BIC criterion [2, 3]
- #(session): 56, mean #(correct trial): 82, mean #(error trial): 22

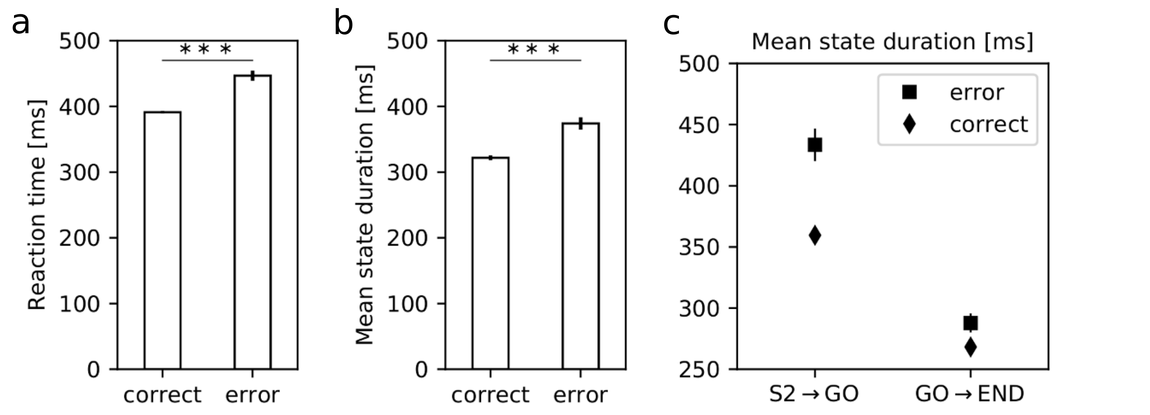
Effect of task difficulty in correct trials:

- *epoch 2*: 400 ms before S2 to 1000 ms after S2
- first transition time after S2 presentation
- $M = 2$
- only session with significant decoding performance
- #(session): 75, mean #(correct trial): 28

④ Results: Mean State Duration in Correct vs. Incorrect Trials

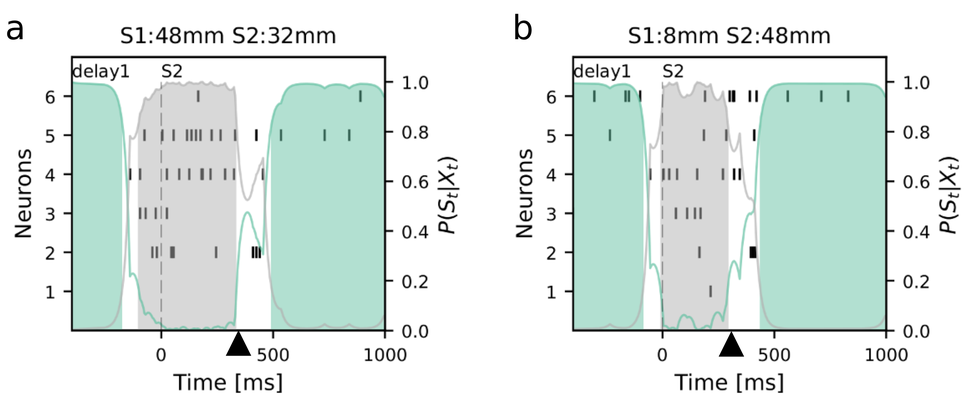


Representative trials of a neural ensemble of 5 cells simultaneously recorded.

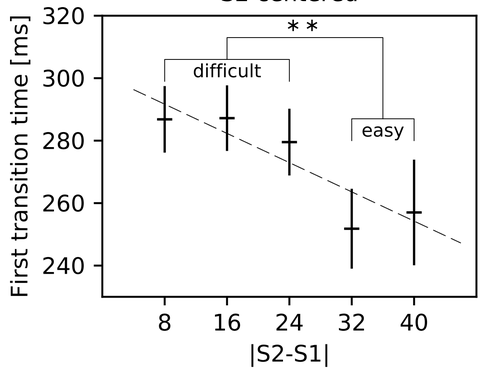


a) and b) $***$ = p<0.001, two-sided Mann-Whitney rank test. c) Two-way ANOVA with factors *trial type* (p<e−12, F(1) = 50.9) and *temporal window* (p<e−79, F(1) = 363.6, p(interaction)<e−05, F(1) = 16.3). Only S2→GO was significant (p< 0.05, Tukey's post-hoc HSD test).

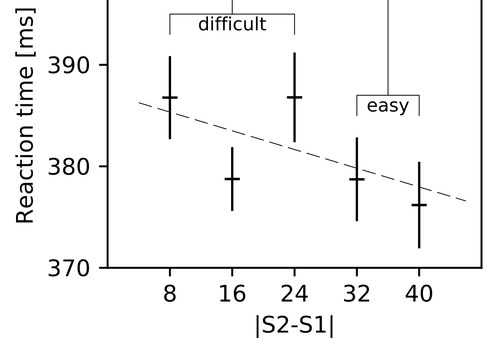
⑤ Results: Neural Correlate of Trial Difficulty



Example trials of a neural ensemble of 6 cells recorded simultaneously. Triangular marker: fTaS2. a: difficult trial $|\Delta S| = 16$. b: easy trial $|\Delta S| = 40$.



Linear regression interpolation (p< 0.05, two-sided Wald test with t-distribution). ** =p< 0.01 two-sided Mann-Whitney rank test.



Linear regression interpolation, p> 0.05 two-sided Wald test with t-distribution). n.s. = not significant two-sided Mann-Whitney rank test.

⑥ Conclusions

- Incorrect responses correspond to a global slow down of the neural dynamics preceding the action and are characterized by a longer reaction time
- Easy correct trials show a faster state shift than difficult correct trials
- Changes in state transitions during target selection and movement preparation, i.e. after GO, do not correlate with trial difficulty

References

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