Analysing neuronal correlates of the comparison of two sequentially presented sensory stimuli

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Scope

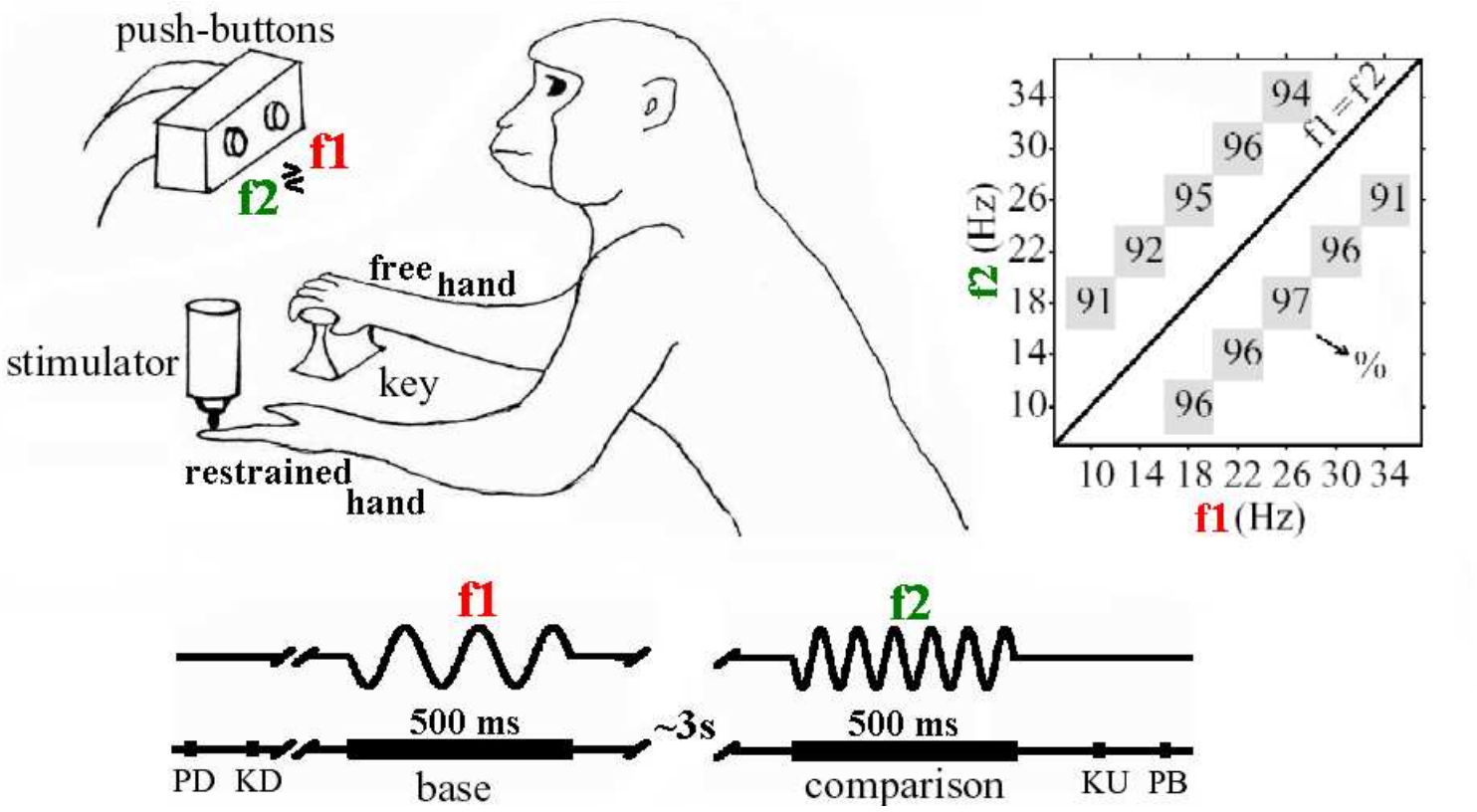
When forming a decision based on sensory information,
where and **how** in the brain do the neuronal responses that encode the sensory stimuli translate into responses that encode the decision

A **two-alternative**, **forced-choice** task is employed.
The subjects must decide which of two mechanical vibrations applied sequentially to their fingertips has the higher frequency of vibration and report their categorical decision by button-press.

- Perception of the 1st stimulus (f1)
- Storage of a stimulus trace in memory
- Perception of the 2nd stimulus (f2)
- Comparison of f2 with the memory trace of f1
- Motor response based on the comparison (f1-f2)

➢ Is S2 a sensory cortex or participates in the decision making ?
(Nat. Neurosci., Nov,2002)

THE TASK



PD: stimulation probe comes into contact with subject's fingertip
KD: free hand touches a key to indicate readiness for the task
KU: free hand leaves the key
PB: and presses one of the two buttons.

- Neurons were recorded from highly trained macaque monkeys
- Vibration freq. was within the "flutter-range" (i.e. 5-50 Hz)

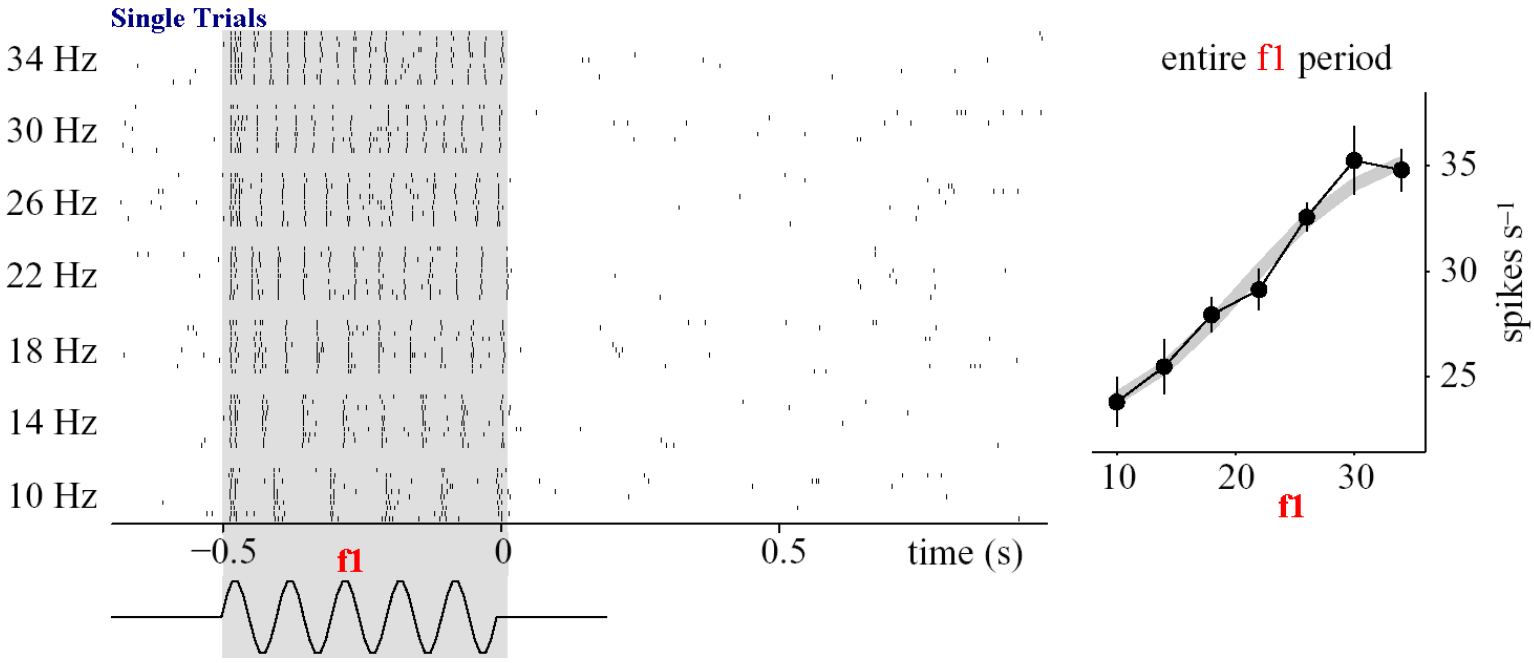
- Perception of f1-stim
  → Primary somatosensory cortex (S1)
- Working memory
  → Inferior convexity of the prefrontal cortex (PFC)
- Perception of the f2-stim
- Comparison of f2 with the memory trace of f1
  → Secondary somatosensory cortex (S2)
- Motor response based on the comparison (f1-f2)
  → Medial premotor cortex (MPC)

RESPONSES during f1 & delay period

➲ Area S1

In columns of rapidly adapting (RA) neurons, the cells respond phasically.

Both the fine temporal structure of the spike trains
and the average firing rate
carry information about the applied stimulus

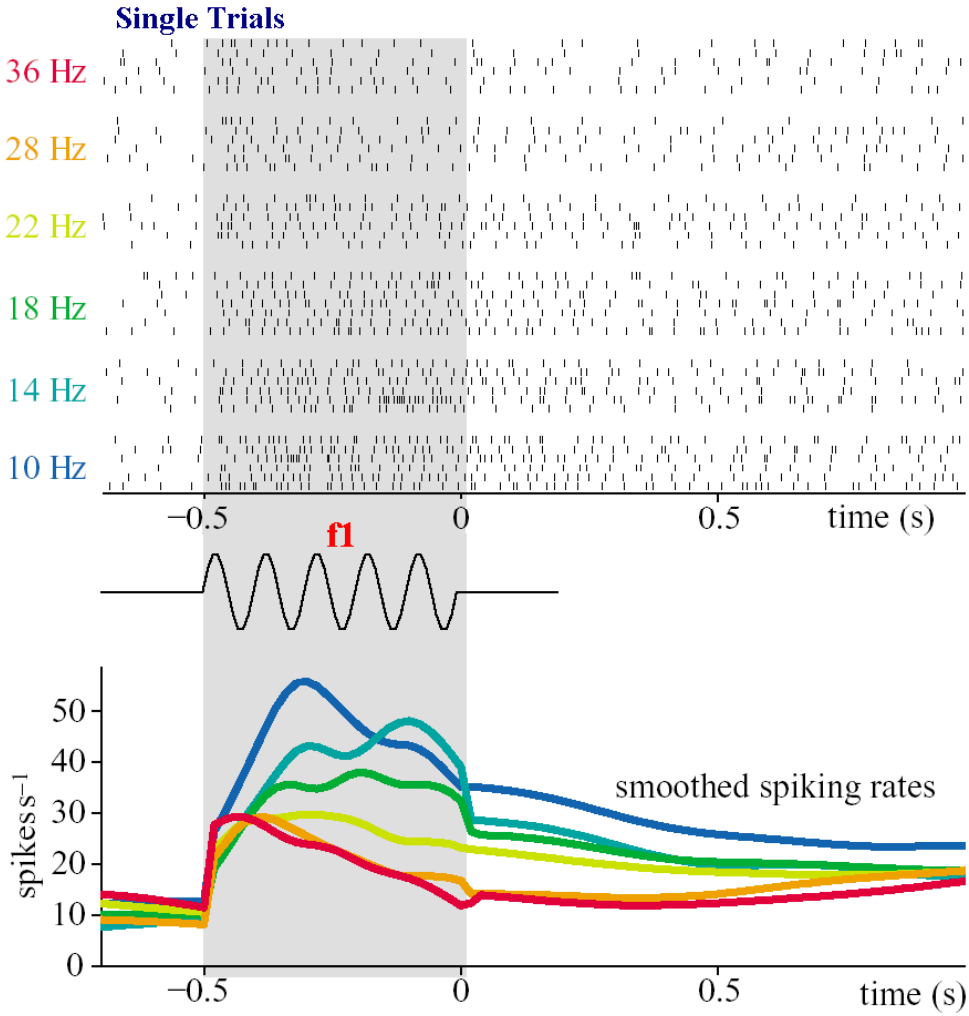


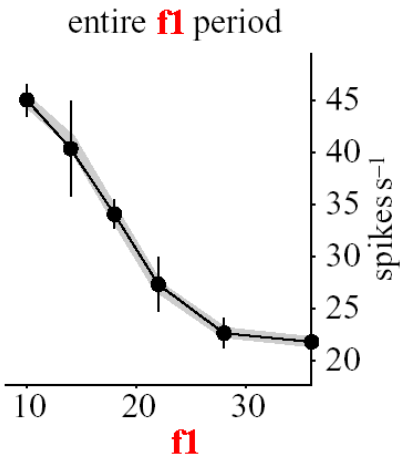
- **There is a positive monotonic relationship between the stimulus and firing rate**

- **The responses stop reflecting information about f1 immediately after the end of the f1-stim**

Area S2

The neurons carry information about f1-stim in the average firing rate,
but not in the fine temporal structure of their spike trains





- **50% of the stimulus-dependent responses are "negative",**
  i.e. there is a **negative** monotonic relationship
  between the stimulus and firing rate

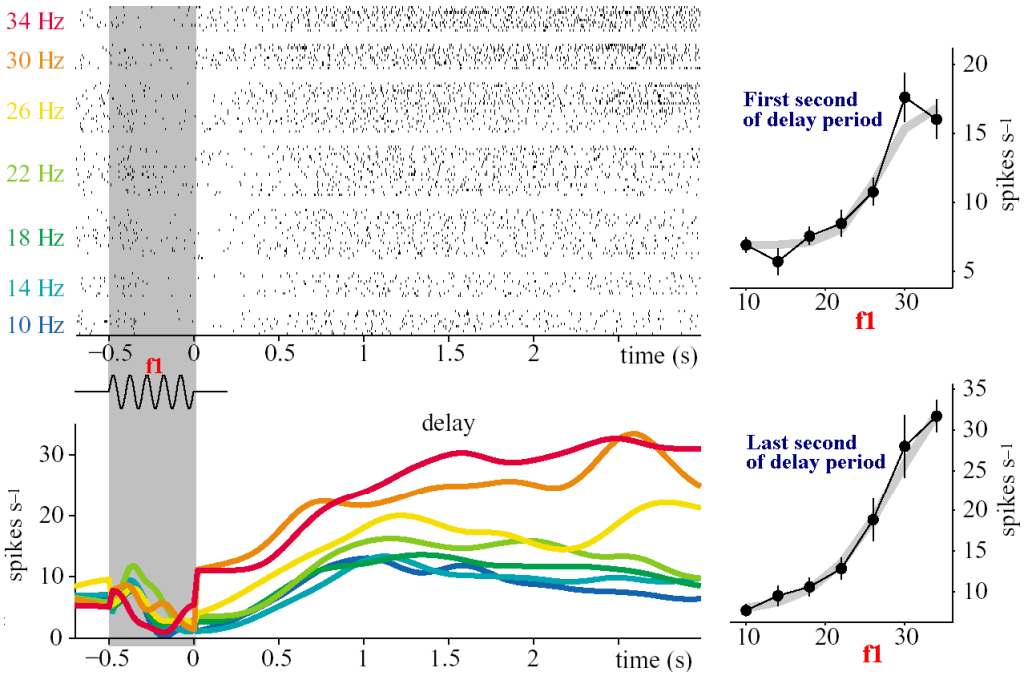
- f1-dependent responses continue for ~500 ms after the f1-stim period
  i.e. S2-neurons keep a memory of the applied stimulus for a short period

However, this period is < than the delay period (~3s)
and therefore the corresponding S2-responses
cannot fully represent the subject's memory

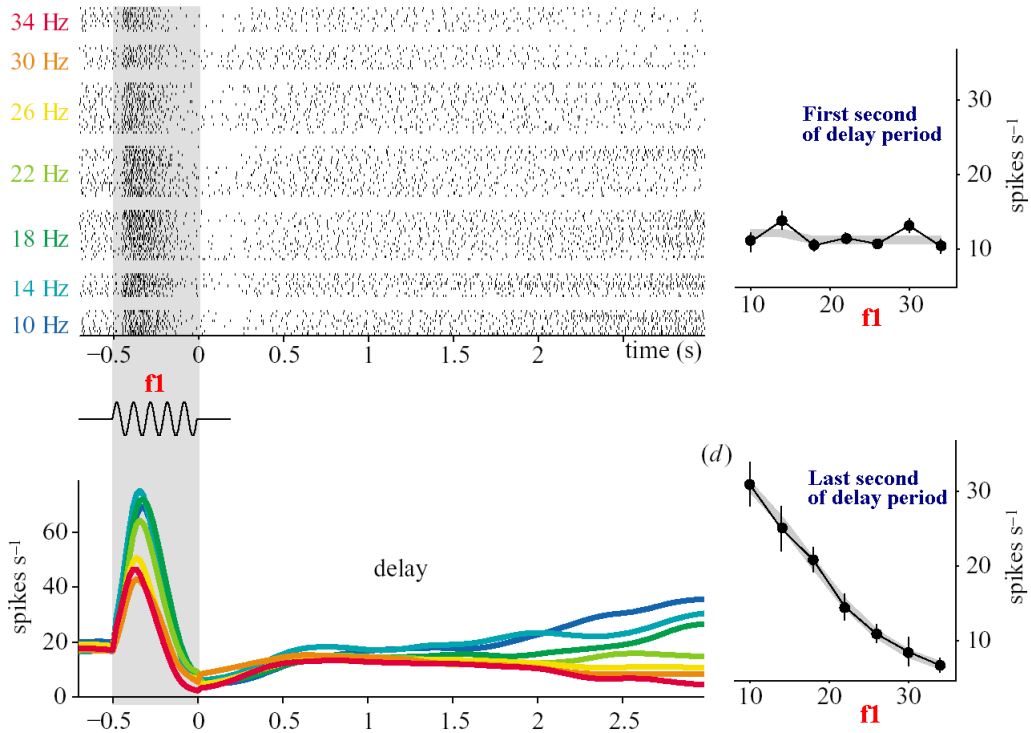
Prefrontal Cortex

Neurons in PFC are the best candidates for the neural substrate
of the subject's short-term memory of f1-stim

Negative and positive monotonic neurons appear in similar numbers.



These neurons present distinct response characteristics.



Responses carry information, in the average firing rate,
about f1-stim into the delay period :
with some neurons (30%) carrying information only during the early part,
others (30%) only during the late part of the delay period,
and still others (25%) throughout the entire delay period.

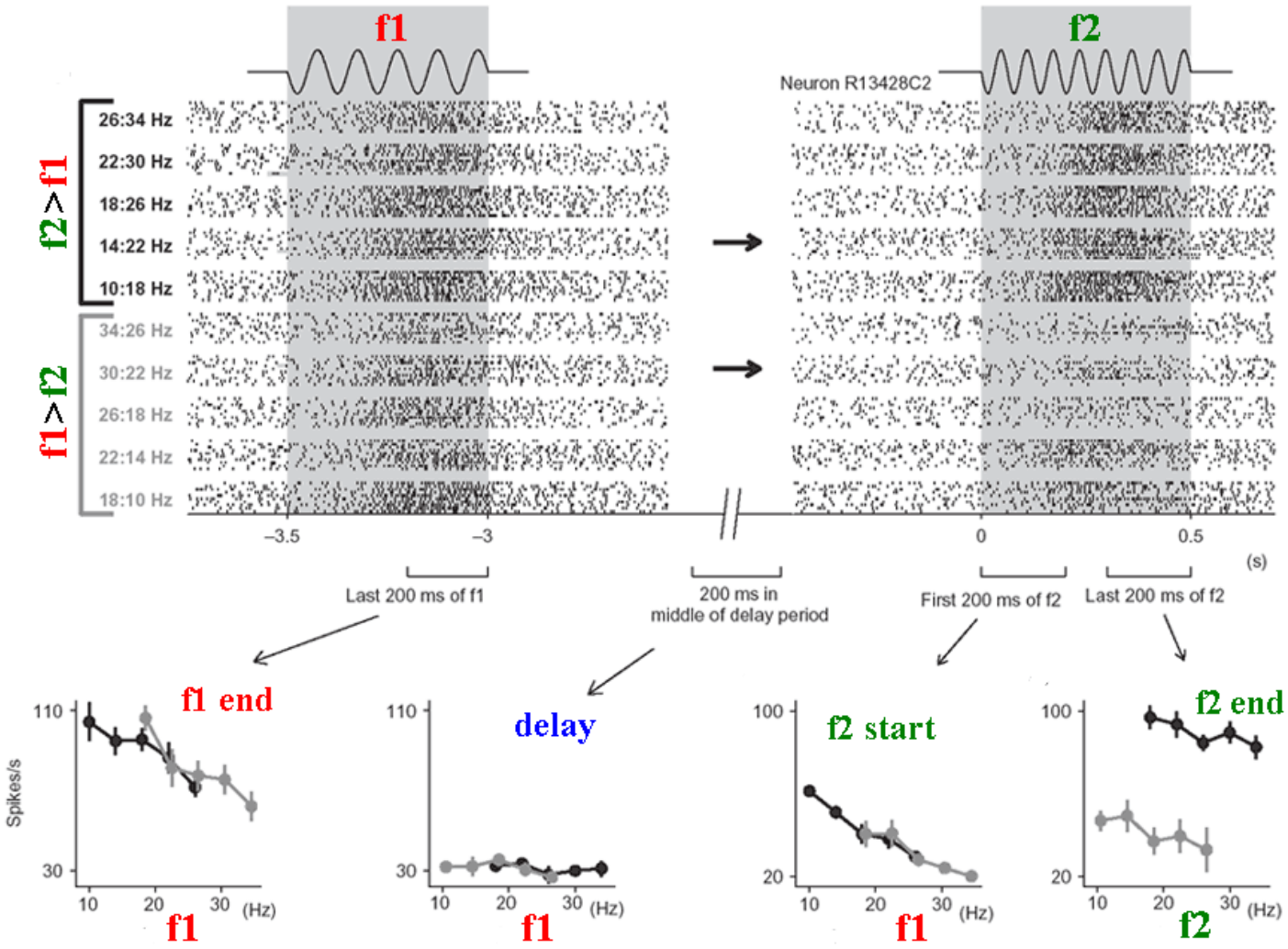
Medial Premotor Cortex

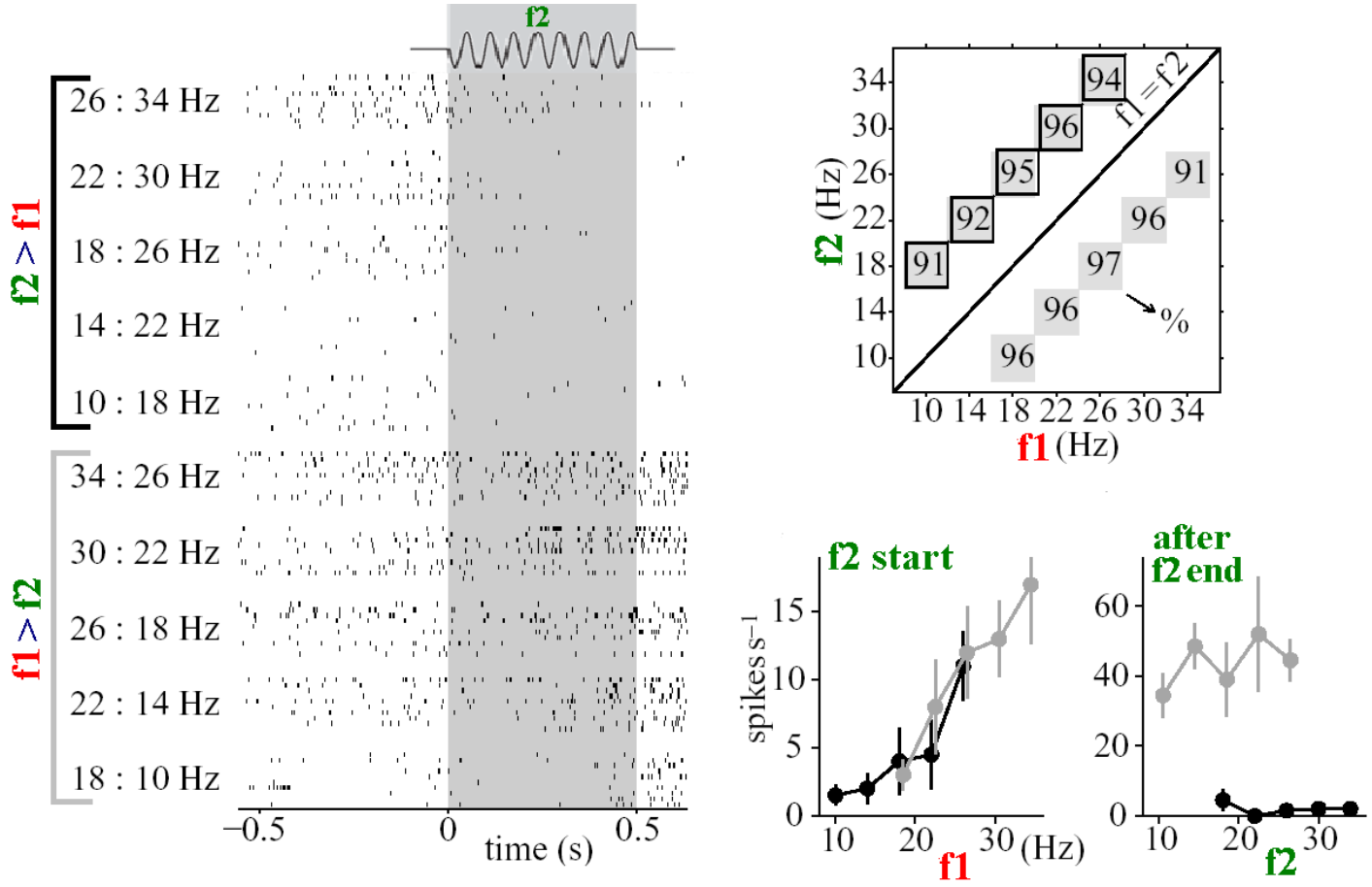
Some MPC neurons respond during f1-stim, with either positive or negative monotonic tuning; and many respond also in a f1-dependent manner during the late part of the delay period.

RESPONSES in area S2 during f2-stim

Upon presentation of **f2-stim** each trial of the task is defined by both **f1** & **f2** parameters.
Responses to **f2-stim** might be influenced by the preceding **f1-stim** especially since the overall task is based on the **f1 / f2** comparison

Trials are divided into two groups: **(i) f2=f1+8 Hz (ii) f2=f1-8 Hz**





- The response to **f2-stim** during the first 200 ms depends on **f1** and not on **f2** :

for a given **f1**, the response was the same regardless of whether **f2>f1** or **f2<f1**

- The response by the end of **f2-stim** has become strongly modulated by both **f1** and **f2**

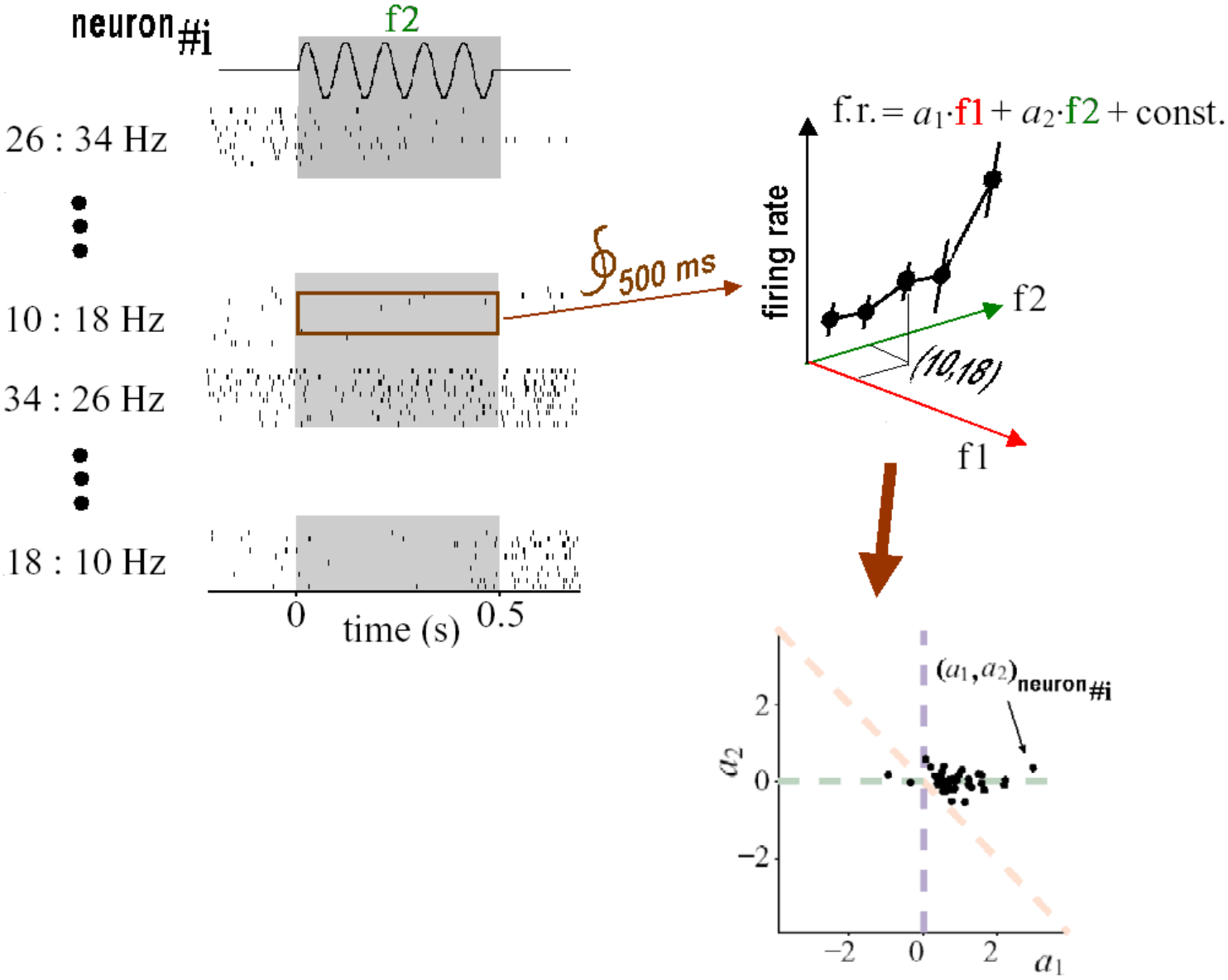
and correlates with the decision which depends only on the ***sign(f2-f1)***

A Linear Modeling of the neural responses

firing rate = α_1 . **f1** + α_2 . **f2** + **const.**

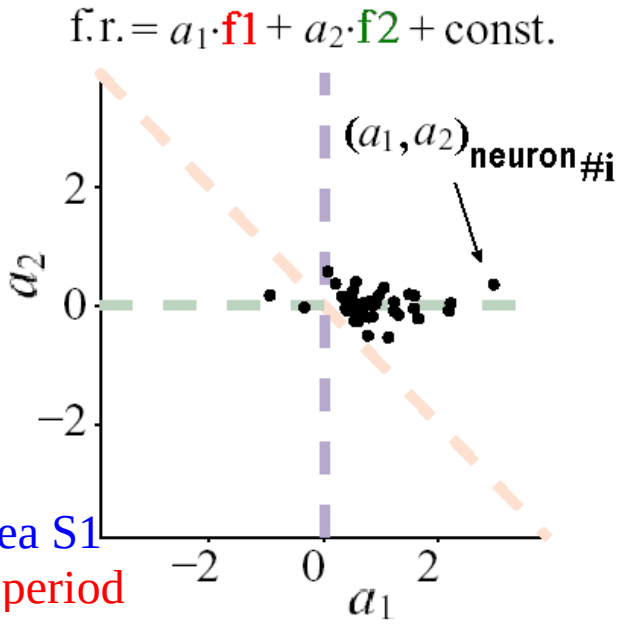
can capture monotonic-trends e.g. f.r. = ct_1 **f1**

and encompasses the "comparison", if $\alpha_2 = -\alpha_1 = ct_2$, f.r.= ct_2 (**f1**-**f2**)



the linear model was fitted to the single-trial responses :

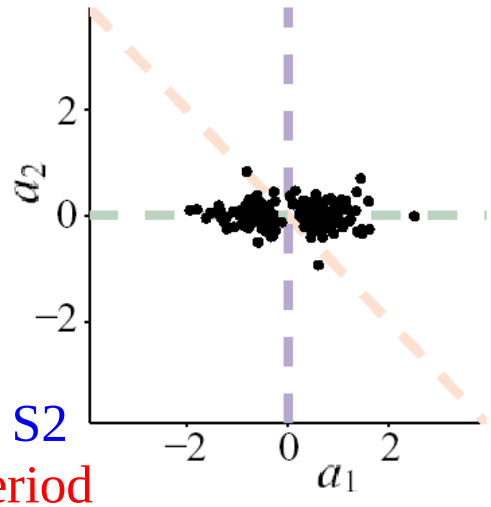
(i) of each of 44 neurons recorded from S1, during **f1-stim** period



Area S1
f1-period

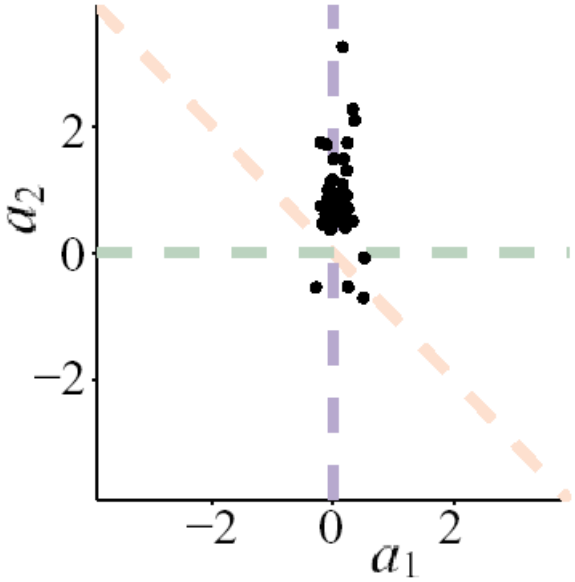
$\alpha_2 \cong 0$,
correctly indicating
independence from f2-stim

(ii) of neurons recorded from S2,
during f1-stim period



Area S2
f1-period

(iii) of neurons recorded from S1,during the **f2-stim** period

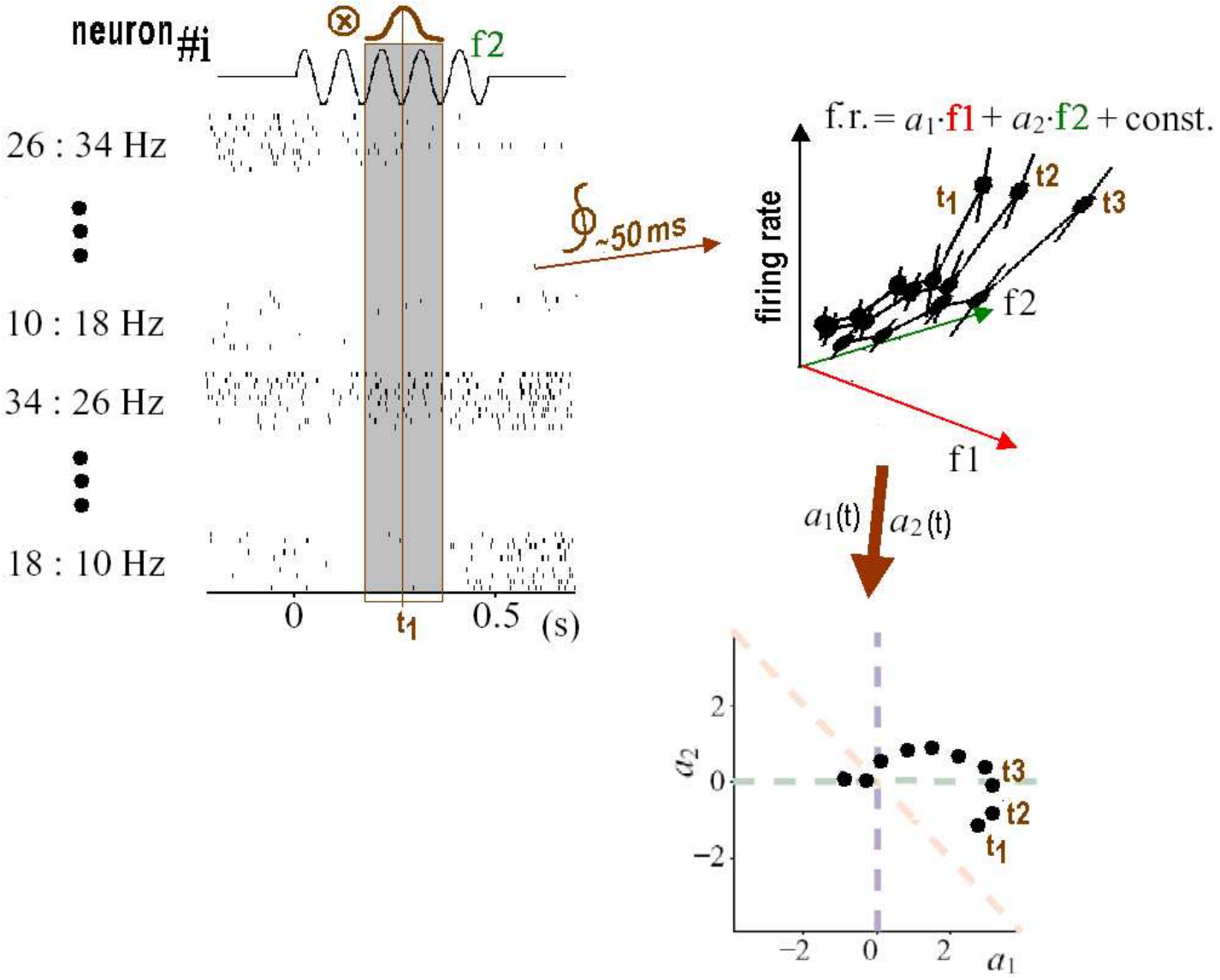


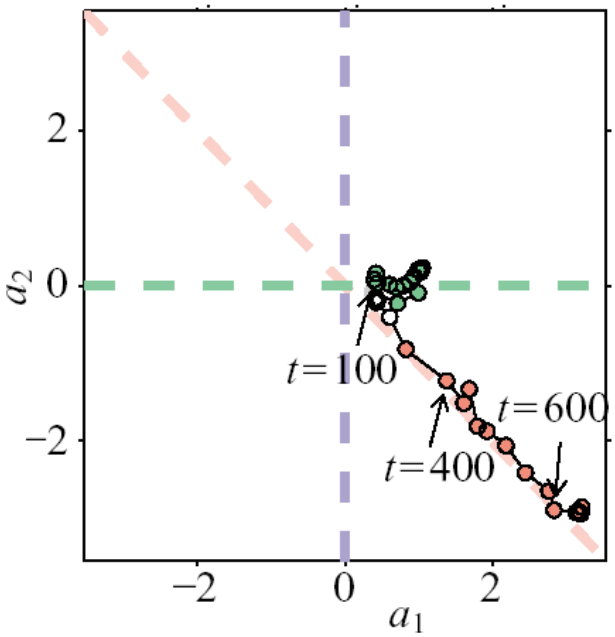
$\alpha_1 \cong 0$,
indicating
independence from f1-stim.

~ S1 is a " purely sensory area "

Time-Dependent Linear Modeling of neural responses

f.r.(t) = $\alpha_1(t)$. f1 + $\alpha_2(t)$. f2 + **const.(t)**



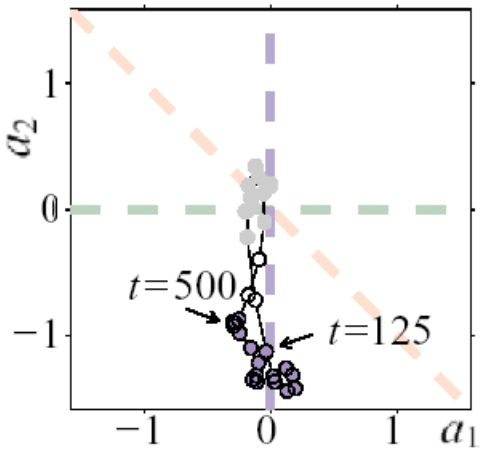


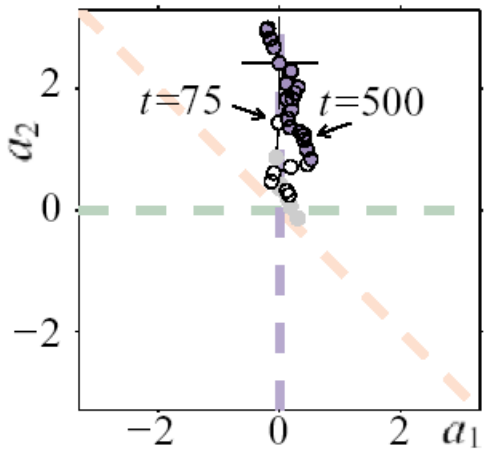
Area S2, f2-stim response dynamics

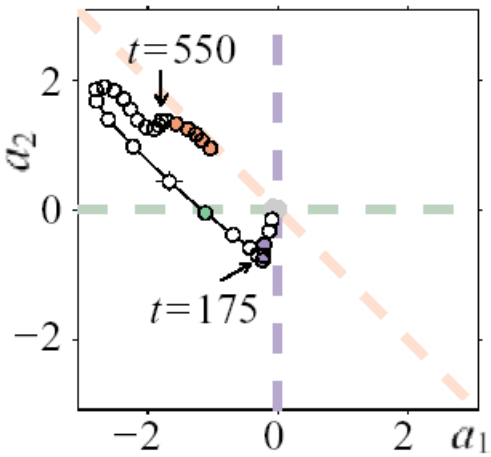
Neuron's firing rate
initially depends on **f1**
but later switches to depending on **f1**-**f2**

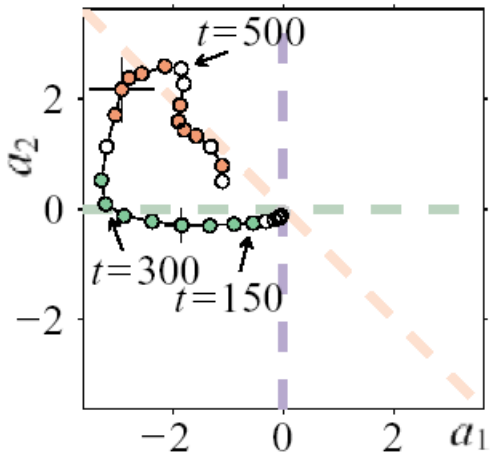
A variety of response dynamics is observed in area S2

Neurons with pure f2-stim dependency



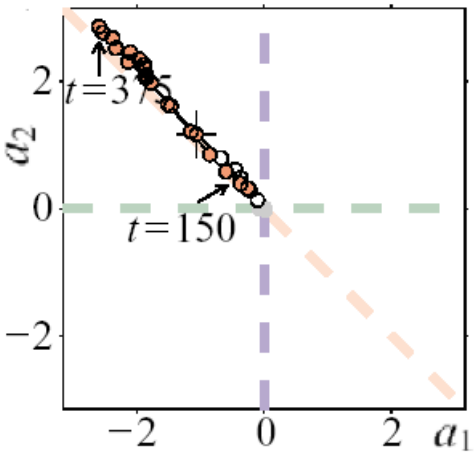


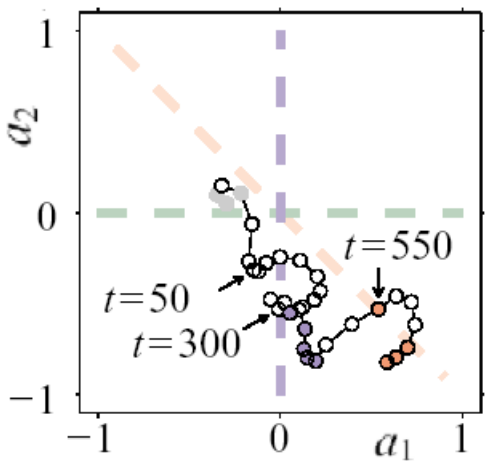


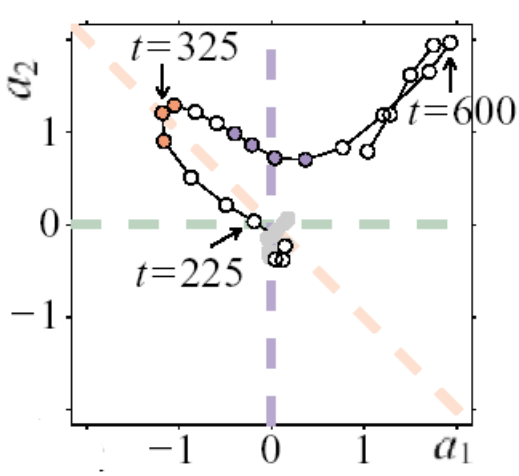


Neurons initially responding to either f2 or f1, yet later becoming (f2-f1) dependent

Neurons depending strictly on (f2-f1) throughout the f2-stim period and into the reaction time after it

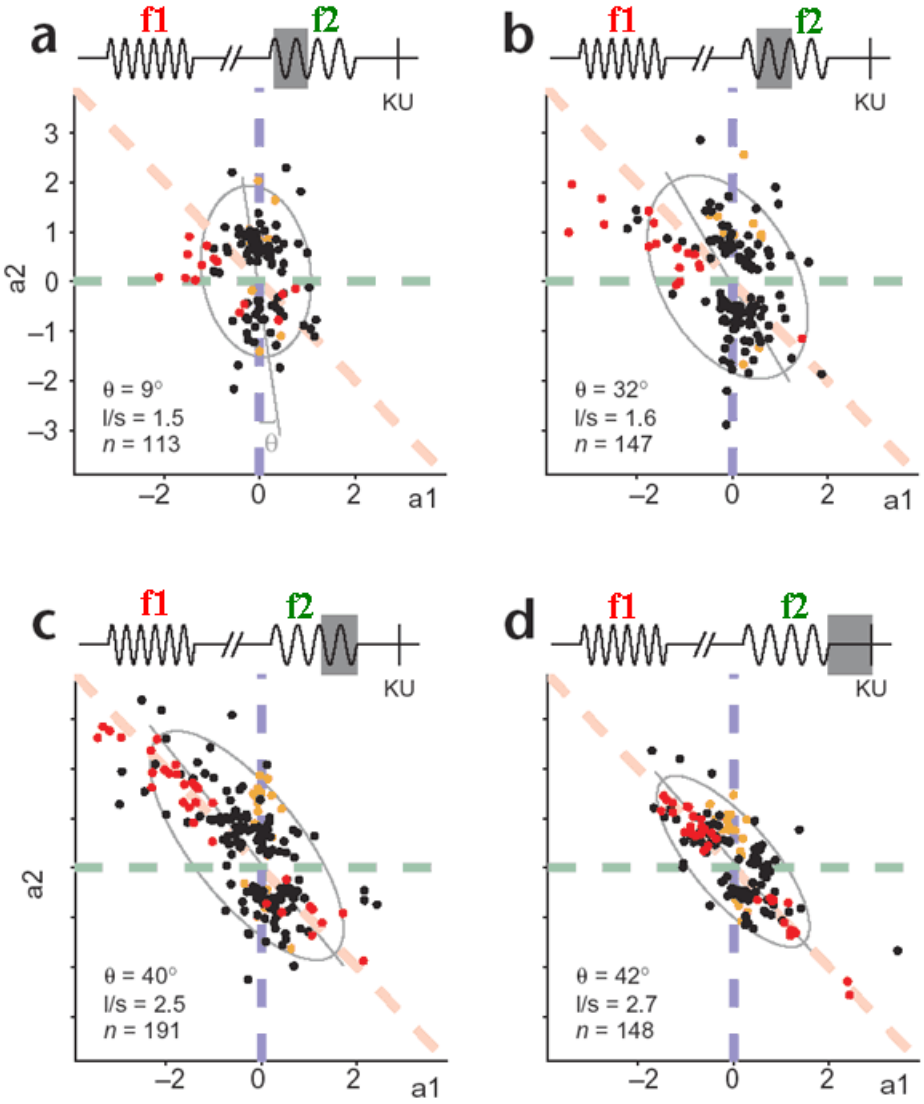






And neurons with response dynamics difficult to be characterized

However, when the population of neurons was analyzed as a whole
it was found that, during the end of **f2-stim** period,
the (f2-f1) trend was the dominant response pattern



[Nat. Neurosci.,Nov_2002]

- out of 517 recorded neurons,
  n=208 were significantly stimulus dependent

-A visual control task verified that there is decision-related activity in S2

- The response latency in S2 is 60 ms shorter
  than response latency in primary motor cortical area M1

CONCLUSIONS

- Neurons in S2 can be modulated by task context
  and display history-dependent responses to somatosensory stimuli

- despite the inter-neuron response-variability, a characteristic population response arises that correlates with the upcoming behavioral decision regarding the ***sign(*** **f2-f1** ***)***

- A variety of brain regions may participate in such decision-producing interactions between current sensory stimuli and short-term memory.

  Similar interactions have been observed in
  medial premotor cortex (MPC) and **prefrontal cortex (PFC)**.

  Choice-correlated responses arise in MPC neurons earlier than S2.
  Choice-related responses can arise in PFC even earlier.

Therefore responses in S2 may reflect the result of a choice that has already been formed elsewhere.