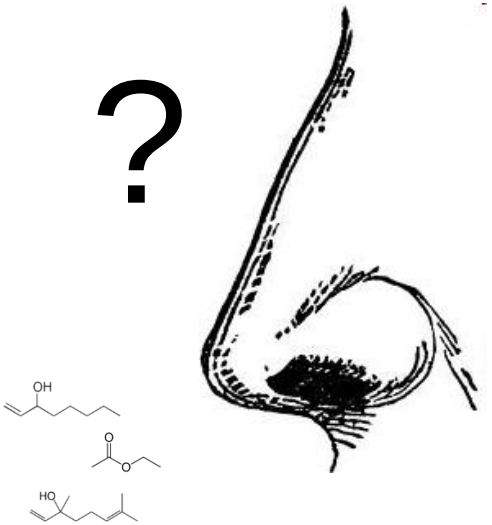


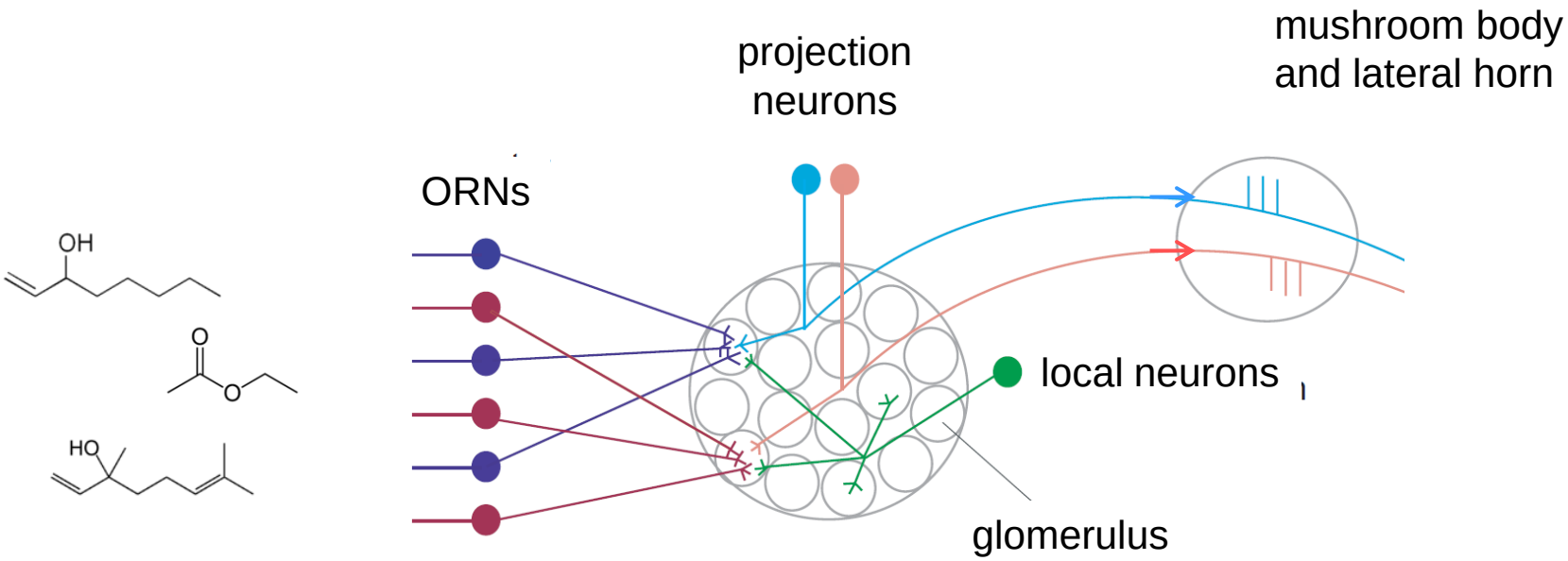
Carlotta Martelli

Stimulus dynamics and odor sensing

thierry.emonet@yale.edu
Molecular Cellular and Developmental Biology & Physics

Martelli C, Carlson J, and Emonet T
Intensity invariant dynamics and odor-specific latencies in olfactory receptor neuron response.
Journal of Neuroscience, 33(15):6285-6297 (2013)

Architecture of the olfactory periphery



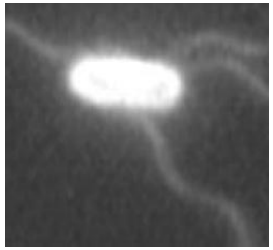
1 receptor ~ 1 neuron ~ 1 glomerulus

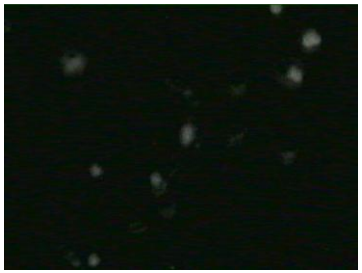
Hallem, Trends in Genetics 2004

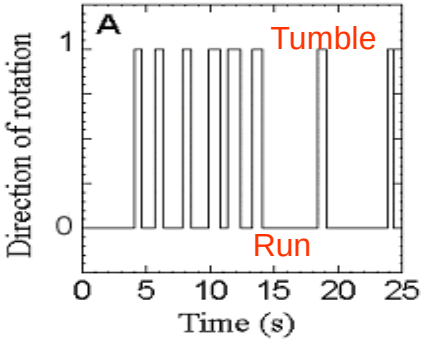
Measurements

Bacterial chemotaxis

Turner et al. 2000





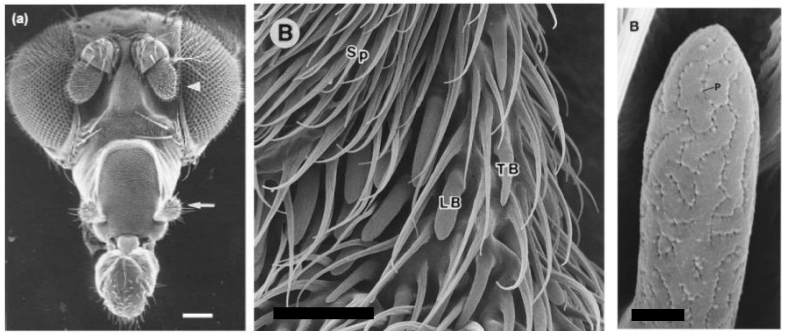


Nature 2004

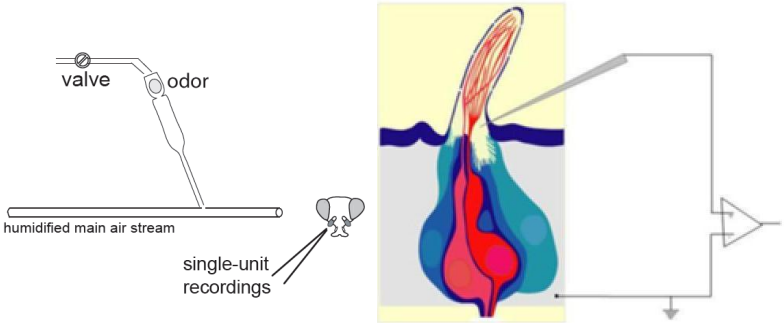
Insect olfaction

Carlson 1996

Shanbhag et al. 1999



100 µm 10 µm 1 µm



Hallem, Carlson (2004)

The combinatorial aspect

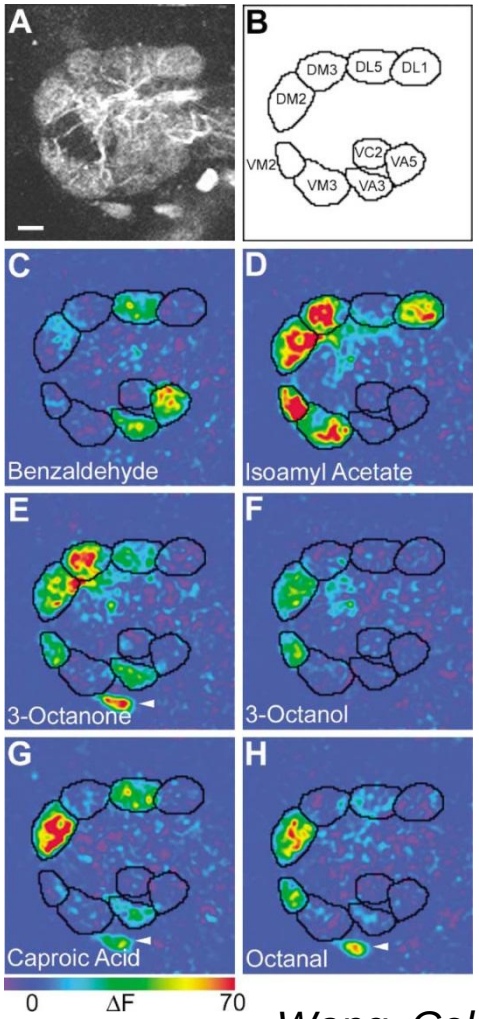
ORNs

glomeruli

odors

	2a	7a	9a	10a	19a	22a	23a	33b	35a	43a	43b	47a	47b	49b	5
ammonium hydroxide	·	–	·	·	·	·	·	·	·	·	·	·	·	·	
putrescine	·	–	·	–	·	·	·	·	·	–	·	·	–	–	
cadaverine	·	–	·	–	·	·	–	·	·	·	·	·	·	·	
γ-butyrolactone	·	·	+	·	·	·	·	·	+	–	·	·	·	·	
γ-hexalactone	·	–	++	·	·	++	·	·	+++	·	·	·	–	·	
γ-octalactone	·	–	·	·	·	·	·	·	·	·	·	·	·	·	
γ-decalactone	·	–	·	·	–	·	·	·	·	–	·	·	·	·	
δ-decalactone	·	–	·	–	–	·	·	·	–	–	·	·	·	–	
methanoic acid	·	–	·	·	·	·	–	·	·	·	·	·	·	·	
acetic acid	·	–	·	·	·	·	·	·	·	·	·	·	·	·	
propionic acid	·	·	·	·	·	·	·	·	·	·	·	·	·	·	
butyric acid	·	·	++	·	·	++	·	·	·	·	·	·	–	·	
pentanoic acid	·	·	·	·	·	·	·	·	·	·	·	·	·	·	
hexanoic acid	·	·	·	·	·	++	·	·	·	·	·	·	–	·	
heptanoic acid	·	·	·	·	–	·	·	·	·	–	·	·	·	·	
octanoic acid	·	·	·	·	–	·	·	–	·	·	·	·	·	·	
nonanoic acid	·	–	·	·	–	·	·	·	·	–	·	·	·	·	
linoleic acid	–	++	·	·	–	·	·	·	·	–	·	·	·	·	
isobutyric acid	·	·	·	·	·	·	·	·	·	·	·	·	·	·	
isopentanoic acid	·	·	·	·	·	·	·	·	·	–	·	·	·	·	
pyruvic acid	·	+	·	·	·	·	·	·	·	·	·	·	·	·	
2-ethylhexanoic acid	·	·	·	·	–	·	·	–	·	–	·	·	·	·	
lactic acid	·	·	·	·	·	·	·	·	·	·	·	·	·	·	
3-methylthio-1-propanol	·	·	+	·	·	·	·	·	+++	·	·	++++	–	·	
dimethyl sulfide	·	·	·	–	–	·	·	·	·	–	·	·	·	–	
terpinolene	–	·	·	·	+	·	·	·	·	·	·	·	·	·	
α-pinene	·	·	·	·	·	·	·	·	·	·	·	·	·	·	
β-pinene	·	–	·	–	·	·	·	·	·	·	·	·	·	·	
3-carene	·	·	·	–	++	·	–	·	·	·	·	·	·	–	
limonene	·	·	·	·	+	·	·	·	+	·	·	·	·	·	
α-humulene	·	·	·	–	·	·	·	·	·	–	·	·	·	·	
β-myrcene	·	·	·	–	·	·	·	·	·	·	·	·	·	·	
(-)-trans-caryophyllene	·	·	·	·	·	·	–	·	·	–	·	·	·	–	
p-cymene	·	·	·	–	·	·	–	·	·	·	·	·	·	·	
geranyl acetate	·	·	·	–	·	·	·	·	·	·	·	·	·	·	
α-terpineol	·	·	·	–	+	+	·	·	·	·	·	·	·	·	
geraniol	·	·	·	·	·	·	–	·	·	–	·	·	·	·	
nerol	·	·	·	–	·	·	·	·	·	·	·	·	·	·	
linalool	·	·	·	–	++	+	·	·	·	·	·	·	·	–	
β-citronellol	·	·	·	–	·	·	–	·	·	–	·	·	·	–	
linalool oxide	·	–	+	·	+	·	·	·	·	·	·	·	·	–	
acetaldehyde	·	+++	+	·	·	+	·	·	·	·	·	+	–	·	
propanal	·	–	·	·	–	·	–	·	·	–	·	·	–	–	
butanal	·	+	·	·	–	+	–	·	+	–	+	·	–	–	
pentanal	·	+++	·	·	–	+	–	·	+	–	·	·	·	–	
hexanal	·	+++	·	·	–	++	·	·	+++	·	·	·	·	·	
E2-hexenal	·	++++	·	–	+	·	·	·	++++	·	+	·	·	·	
furfural	·	+++	+	·	–	·	·	·	+++	–	·	·	·	·	
2-propenal	·	·	·	·	·	·	–	·	–	·	·	·	·	·	
acetone	·	–	·	·	–	·	–	·	·	–	·	·	·	·	
2-butanone	·	·	+	·	–	+	·	·	·	·	·	·	·	·	
2-pentanone	·	·	++	·	·	++	·	·	++	·	+	+	–	·	
2-heptanone	·	·	++	·	++	++	·	·	++	·	+	++++	·	·	
6-methyl-5-hepten-2-one	·	–	+	·	+	+	·	·	–	·	·	·	·	–	
2,3-butanedione	·	·	+	·	·	·	·	·	·	·	+	·	·	·	
phenethyl alcohol	·	·	·	–	·	·	·	·	++	·	·	·	·	·	
benzyl alcohol	–	·	·	·	·	·	–	·	·	+	·	·	·	++	
methyl salicylate	·	·	·	++++	·	·	·	·	·	·	·	·	·	·	
methyl benzoate	·	–	·	++++	·	·	–	·	–	·	·	·	·	·	
ethyl benzoate	·	–	·	++++	·	·	–	·	–	–	·	·	·	–	
phenethyl acetate	·	–	·	–	·	·	·	·	–	–	·	·	·	·	
benzaldehyde	·	++++	+	++	–	·	–	·	+	·	·	·	·	++	
phenylacetaldehyde	·	·	·	+	–	·	·	·	–	·	·	·	·	+	
acetophenone	·	·	+	++++	·	·	–	–	·	·	·	·	·	+	
ethyl cinnamate	–	·	·	·	–	·	·	·	–	–	·	·	·	·	
2-methylphenol	–	–	·	–	–	·	–	–	–	+	·	·	–	++++	
4-ethylguaiacol	·	–	·	·	·	·	–	·	·	·	·	·	·	·	
eugenol	·	–	·	+	–	·	·	·	·	–	·	·	·	–	

Hallem, Cell 2006

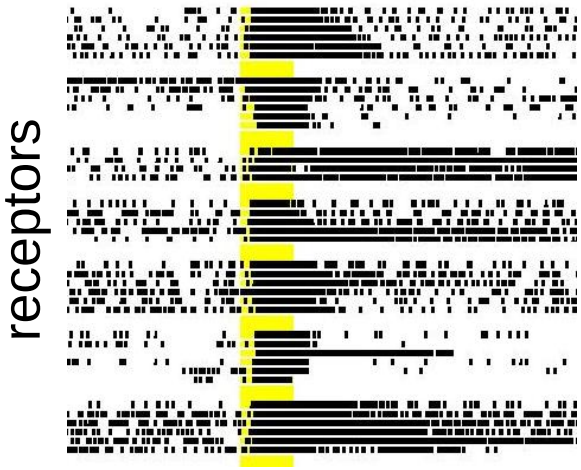


Wang, Cell 2003

The temporal aspect

ORNs

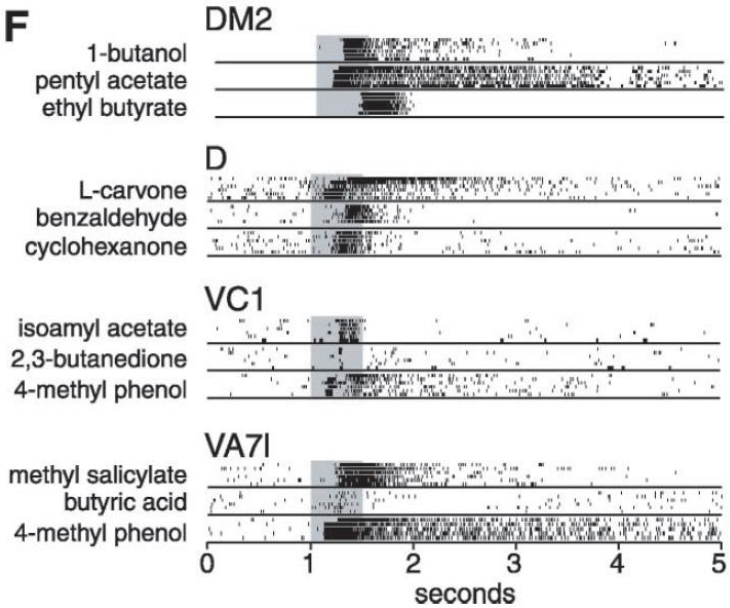
same odor



Hallem, Cell 2006

See also Nagel and Wilson Nature Neuro 2011

Projection Neurons



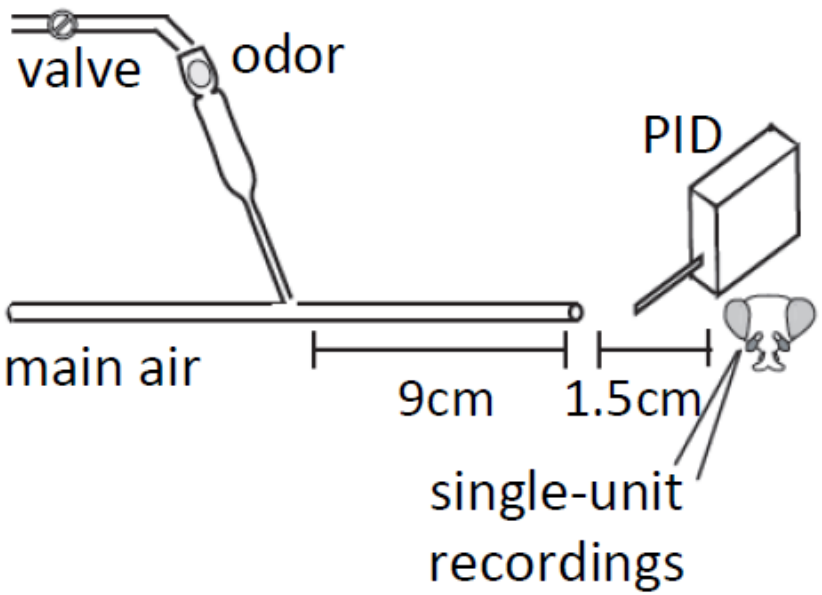
Wilson, Science 2004

Stopfer et al. Neuron 2003
Raman et al, J. of Neuro. 2010

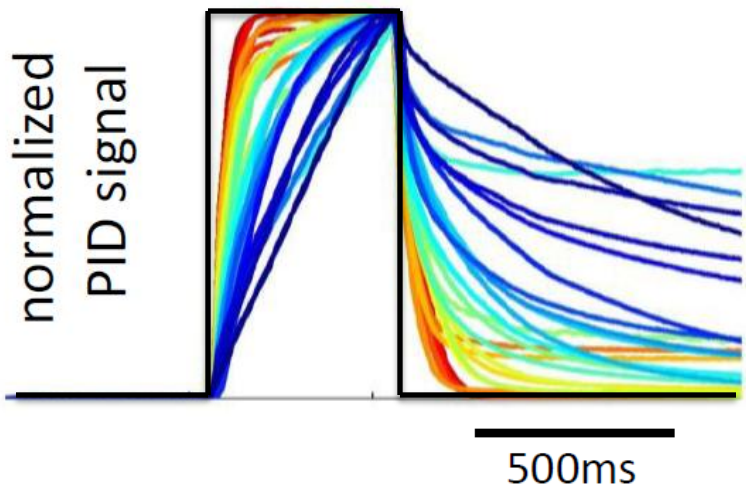
how do ORN response **dynamics** depend
on odor intensity and
on odor identity?

A framework to analyze ORN dynamics

quantify odor stimulus



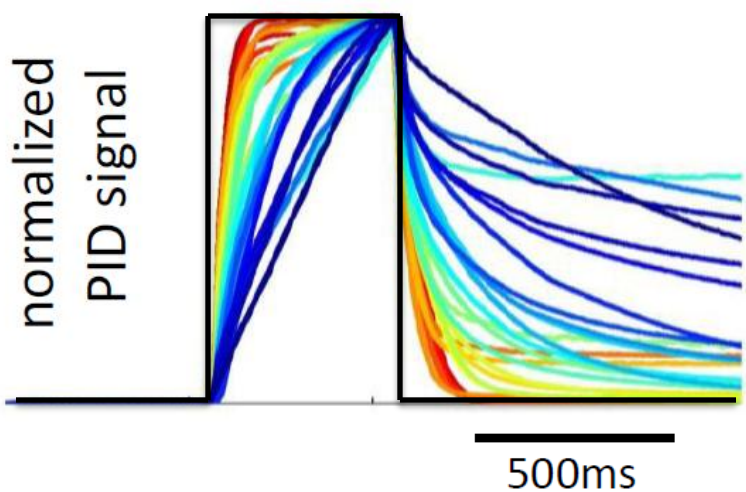
stimulus dynamics…

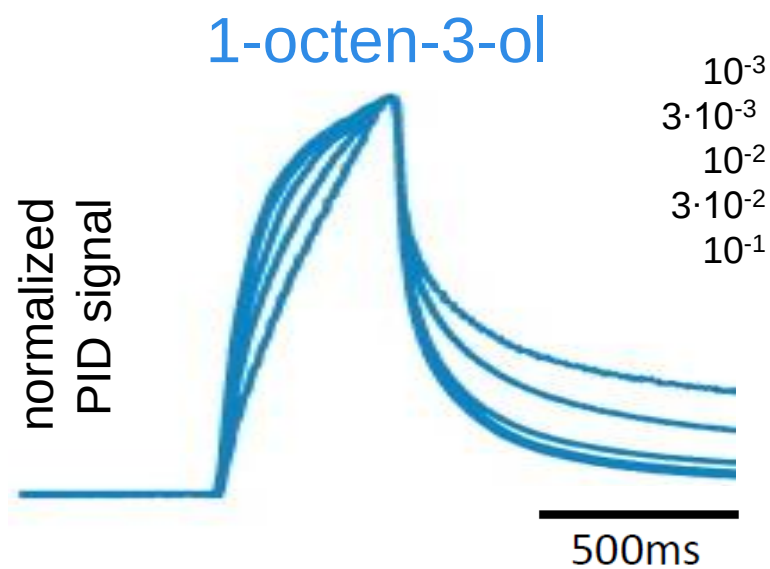


τ ~ 3ms to 1sec

…depends on odor identity

stimulus dynamics…





τ ~ 3ms to 1sec

…and on odor concentration

Transport equations are **linear** in the odor concentration. Where does the dependency on concentration comes from?

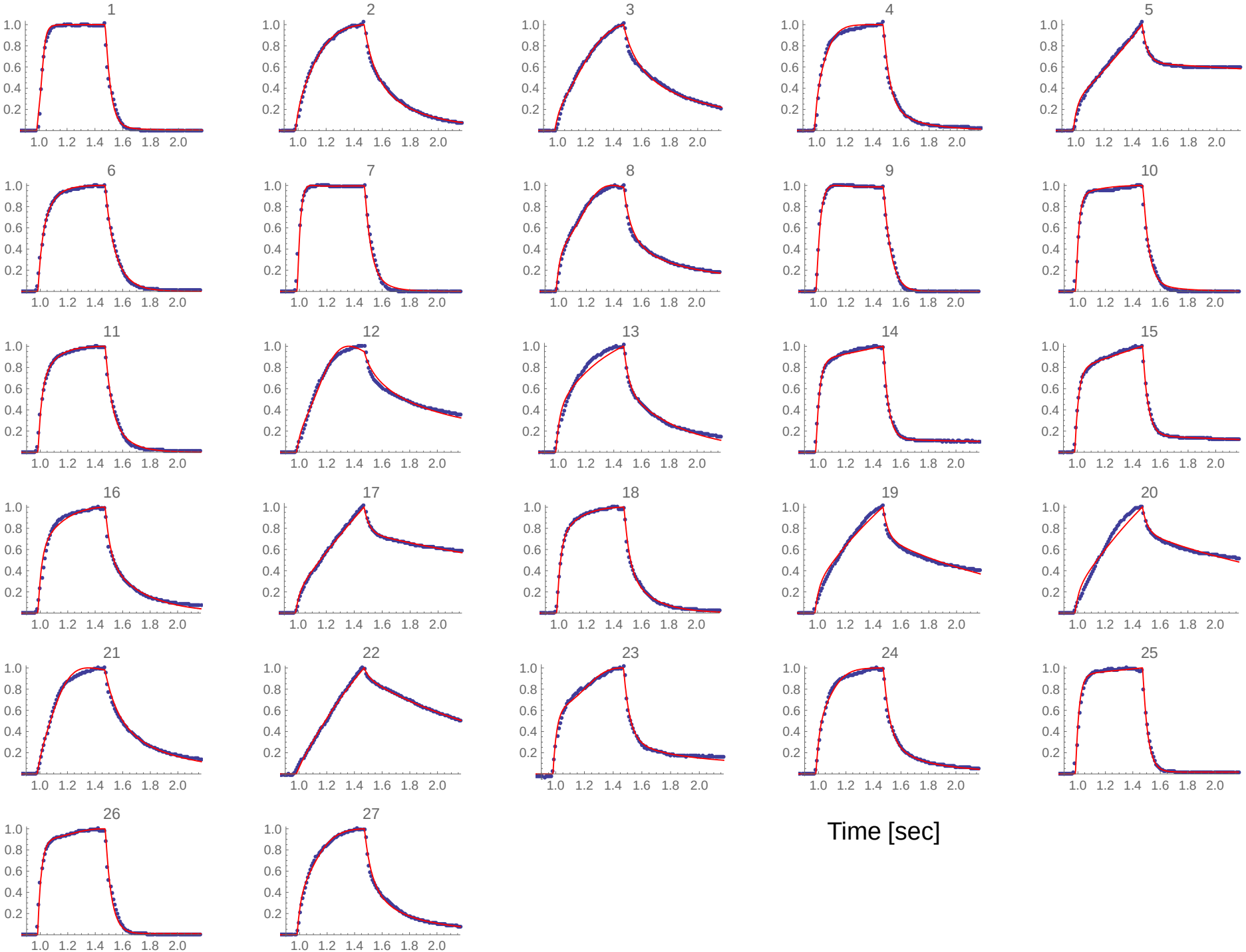
Surface interactions

$$\partial_t c = -(1-\Phi)c + \Phi c_0 - \frac{2w}{r}\partial_t q$$

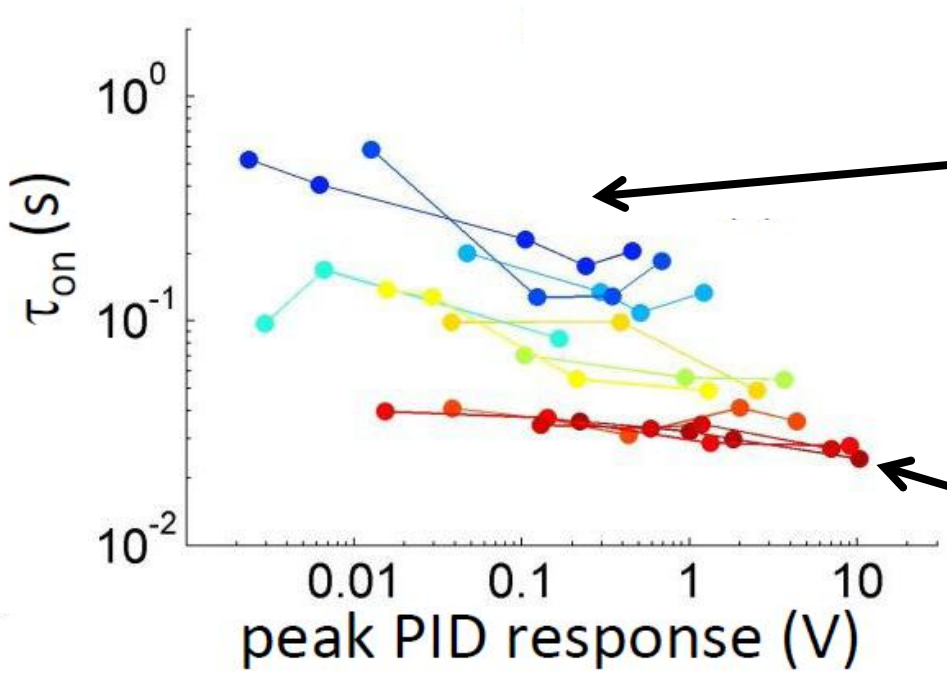
$$\partial_t q = k_a c(1-q) - k_d q$$

Assume interactions are fast

$$\left(1 + \frac{2w/(rK_d)}{\left(1 + c/K_d\right)^2}\right)\partial_t c = -\left(1+\Phi\right)c + \Phi c_0$$

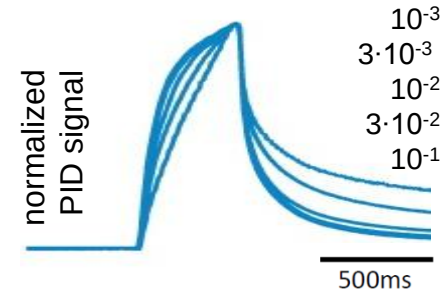

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
1.0
0.8
0.6
0.4
0.2
1.0 1.2 1.4 1.6 1.8 2.0
Time [sec]

stimulus dynamics depend on odor identity and concentration



"slow odor"

1-octen-3-ol

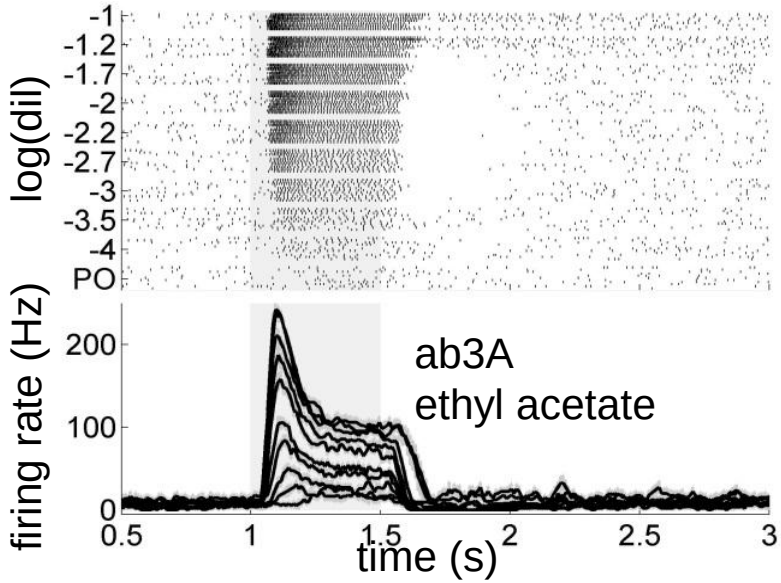


"fast odor"

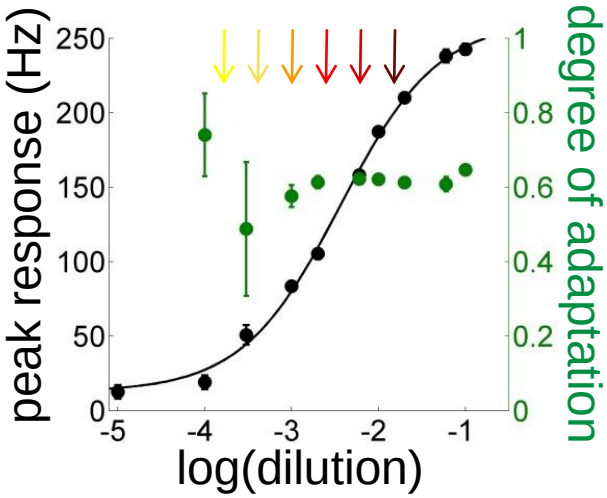
methyl butyrate

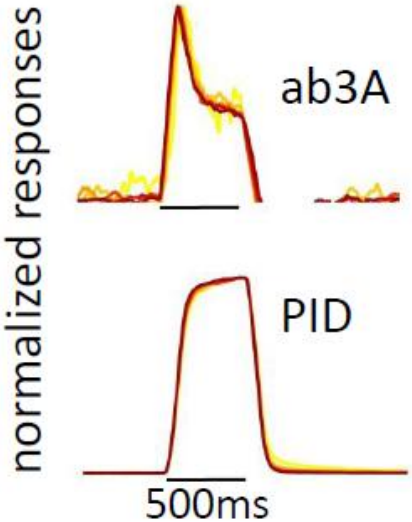
How do ORN response **dynamics** depend on the intensity of a **“fast”** odorant?

Dependence on odor concentration



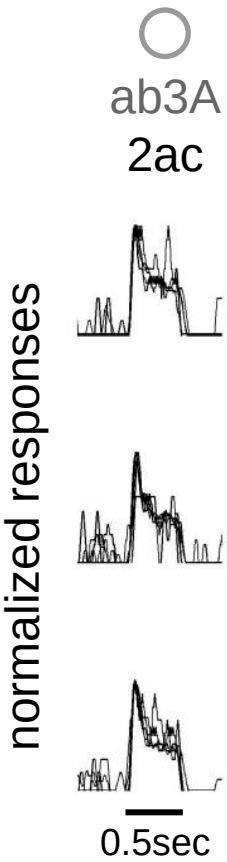
concentration dependent

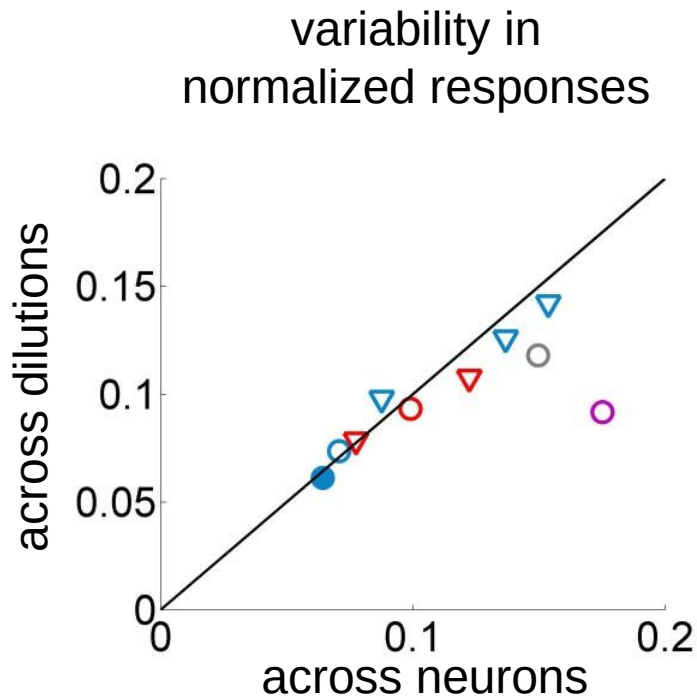




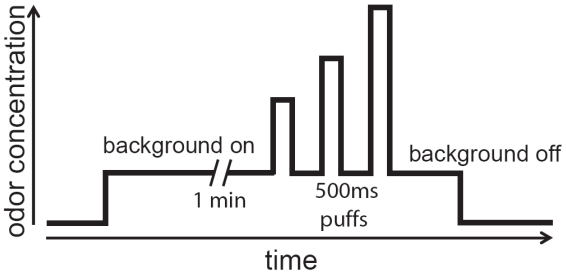
concentration independent

The response dynamics of *individual* ORN exhibit invariance with respect to odor concentration





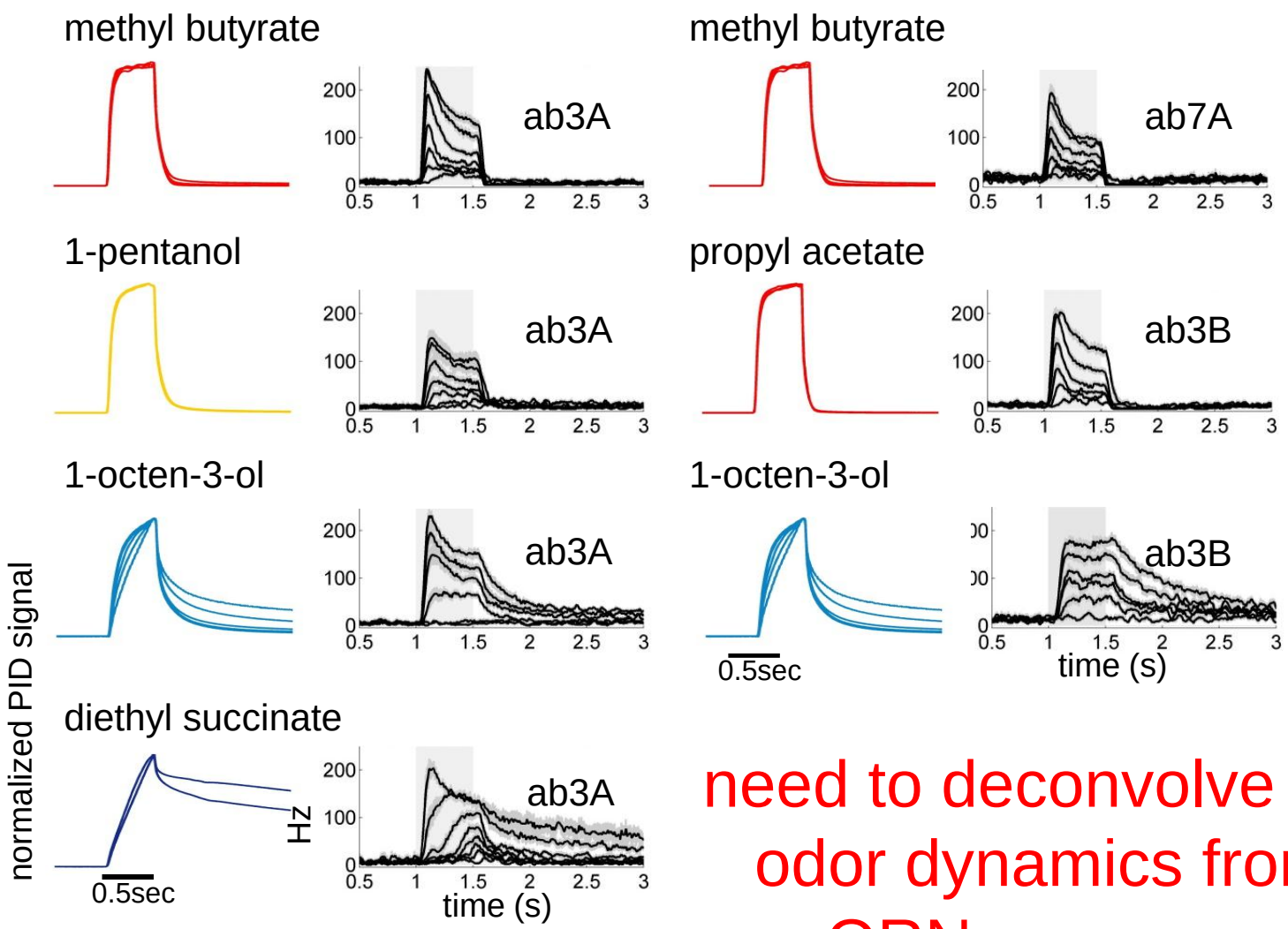
What if there is a background?



Response amplitude increases with stimulus intensity

Response **dynamics** exhibits some invariance to stimulus and background intensity

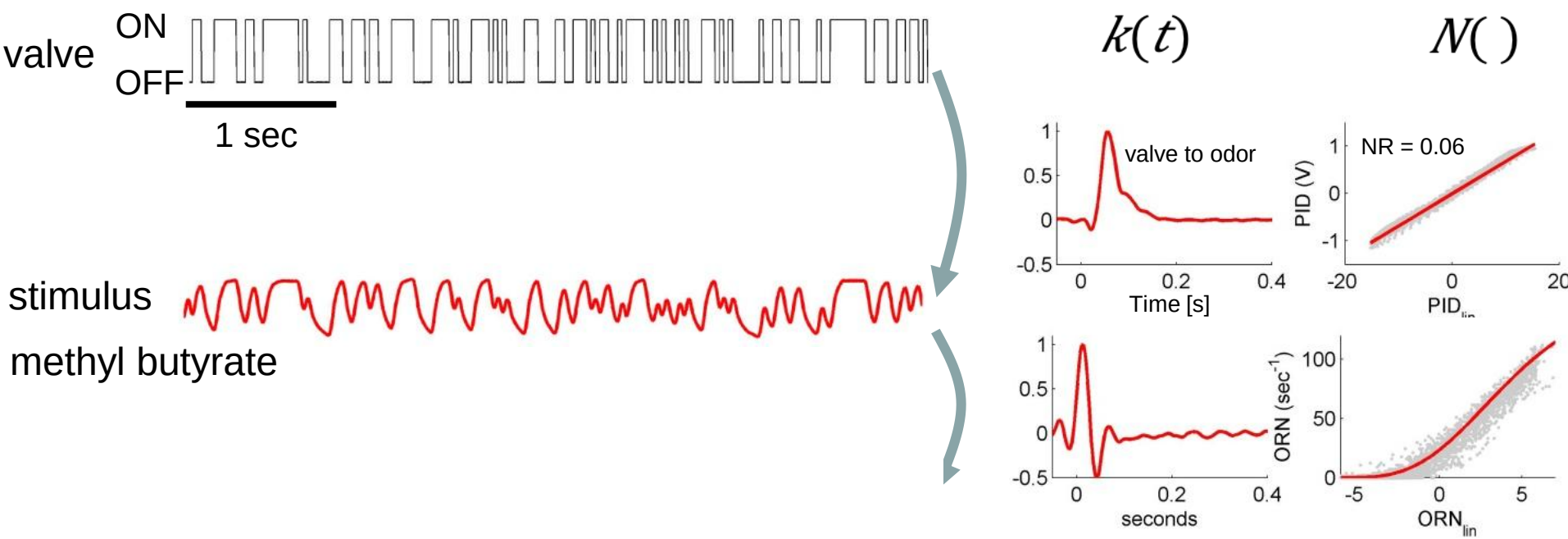
Response to different odorants



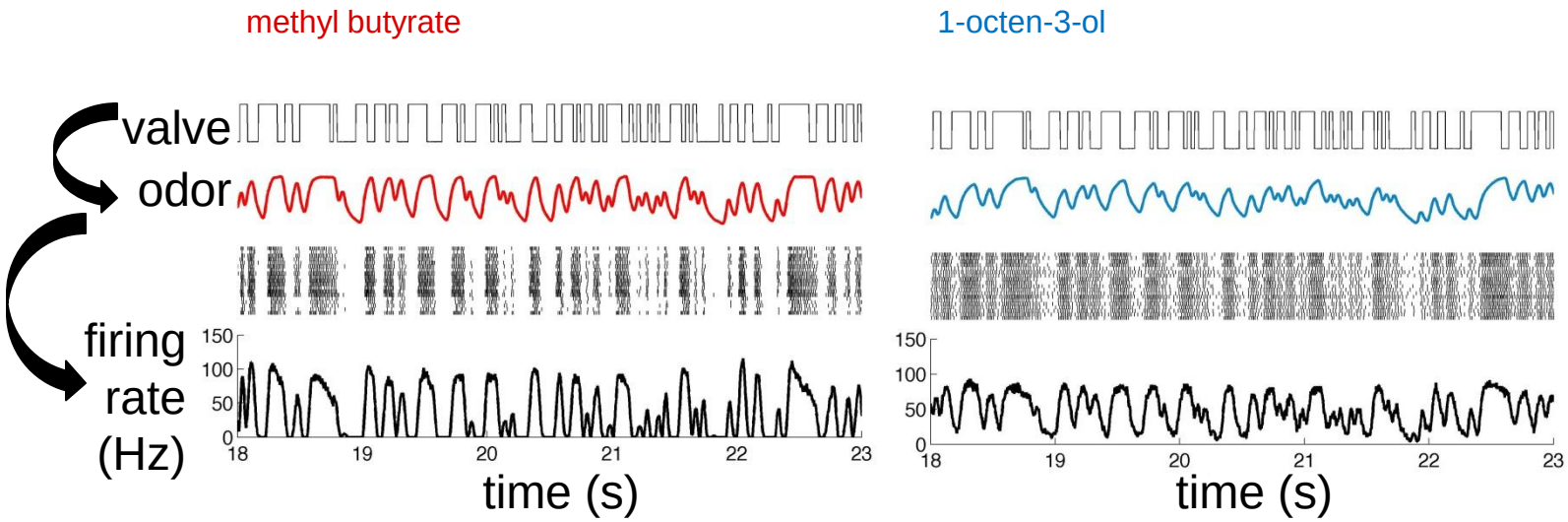
need to deconvolve the odor dynamics from ORN response

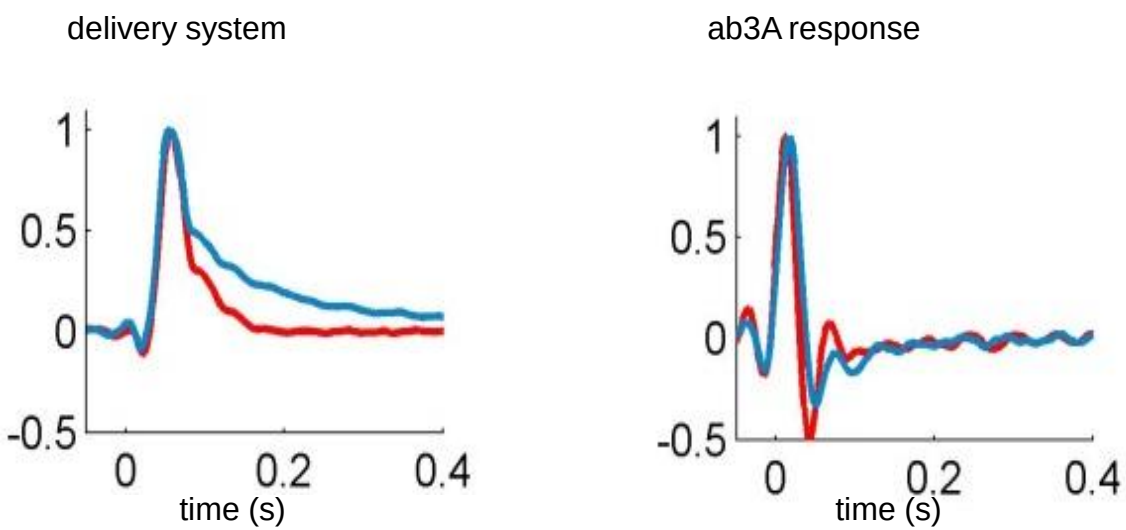
model for ORN response

$$\text{firing rate} = N(k * \text{stimulus})$$



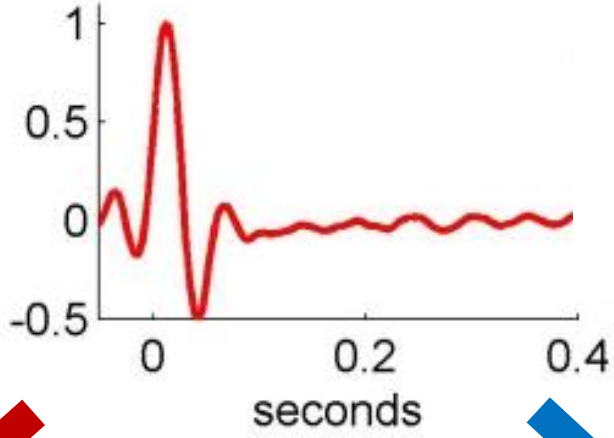
response function to slow and fast odors



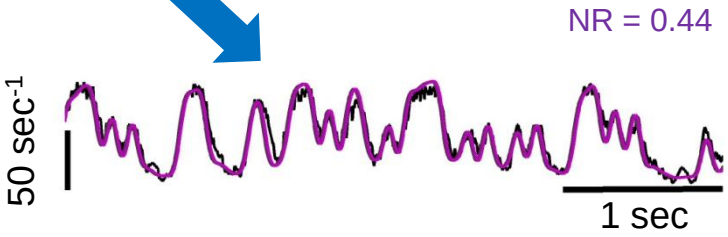


Fast odorant
methyl butyrate stimulus (PID)

Slow odorant
1-octen-3-ol stimulus (PID)



One filter mediates the response of ab3A to two odors



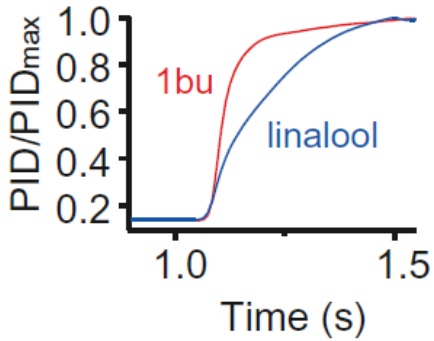
Large differences in stimulus dynamics can dominate the response

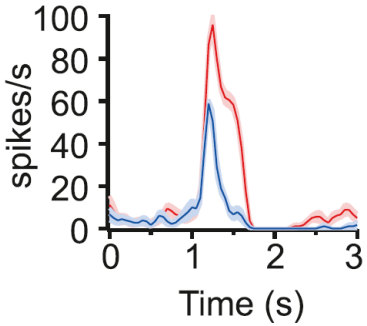
Odor-dependent dynamics can shape ORN response to mixtures of excitatory and inhibitory odorants.

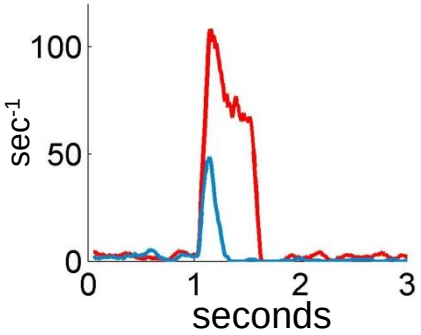
Simulation with LN-Poisson cascade using ab3A LN model

fast excitatory + slow inhibitor

ab2A
1bu (10^{-3})+PO
1bu (10^{-3})+ Lin(10^{-1})

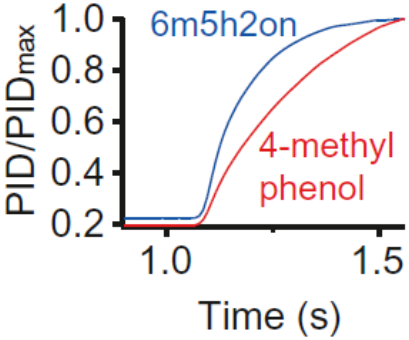


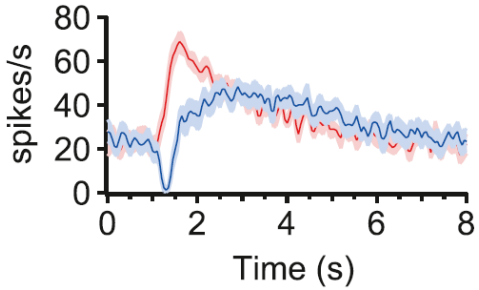


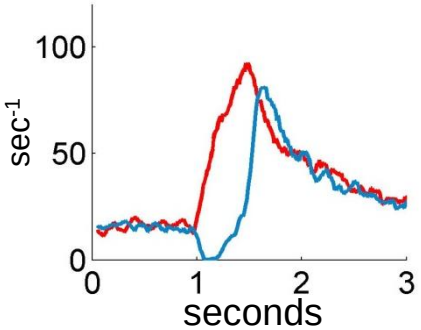


slow excitatory + fast inhibitor

AgOr1 in empty neuron
4-methylphenol (10^{-5}) + PO
4-methylphenol (10^{-5}) + 6m5h2on (10^{-1})

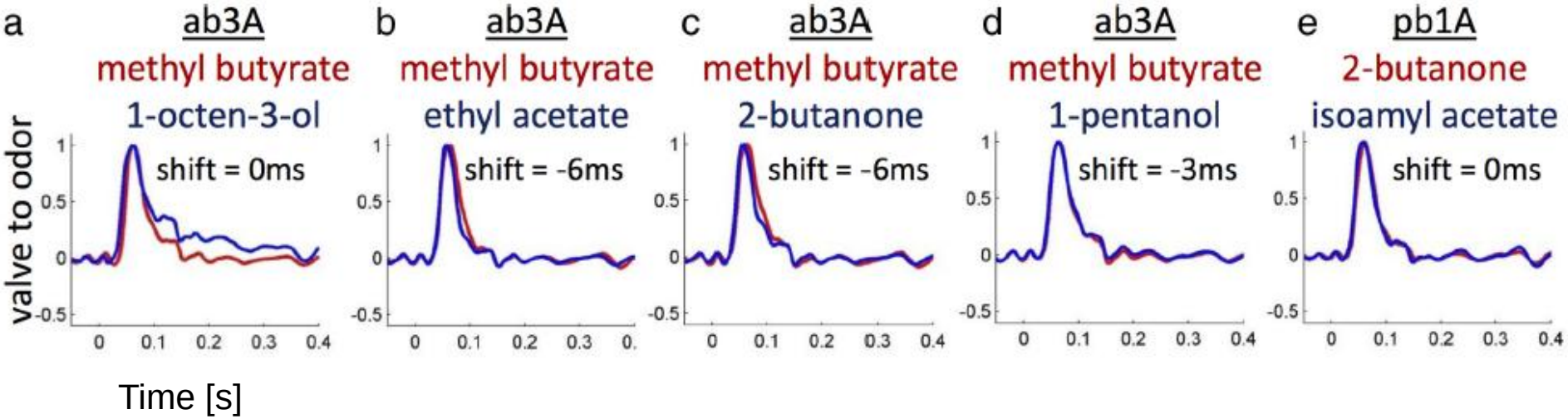




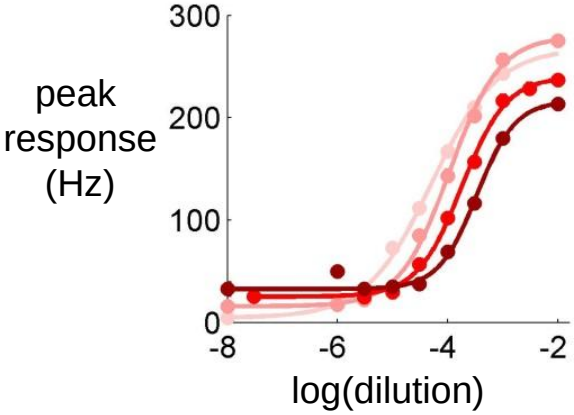


Su, Martelli et al. PNAS 2011

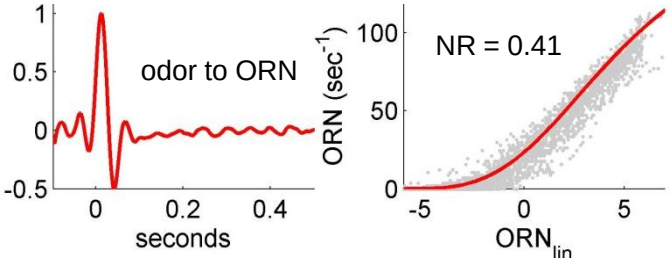
How does the physiological response depend on odor identity?


a
ab3A
methyl butyrate
1-octen-3-ol
shift = 0ms
b
ab3A
methyl butyrate
ethyl acetate
shift = -6ms
c
ab3A
methyl butyrate
2-butanone
shift = -6ms
d
ab3A
methyl butyrate
1-pentanol
shift = -3ms
e
pb1A
2-butanone
isoamyl acetate
shift = 0ms
valve to odor
Time [s]

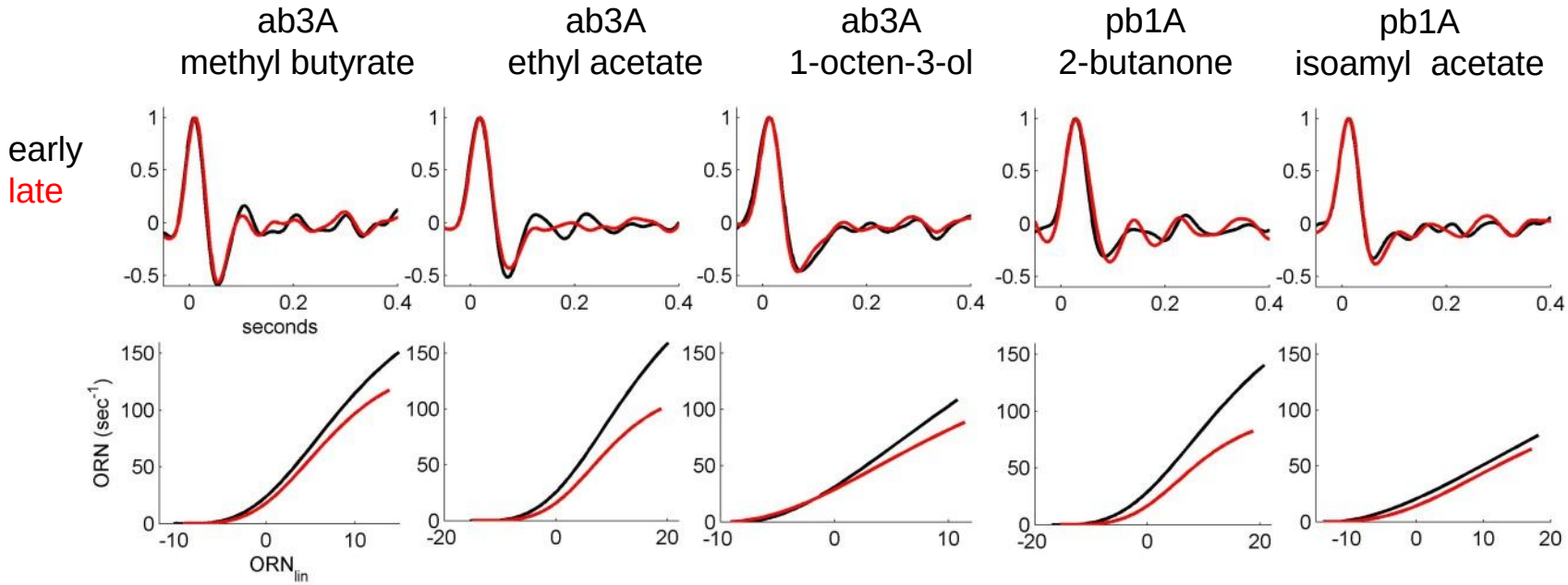
How does adaptation affects the response function?



?



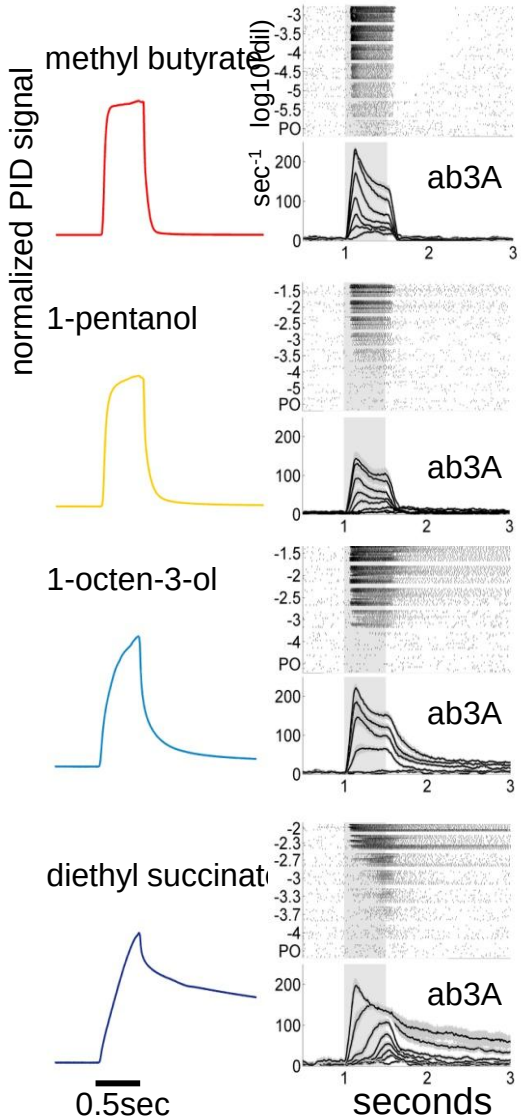
Compare ORN response at the beginning and end of the flickering stimulus

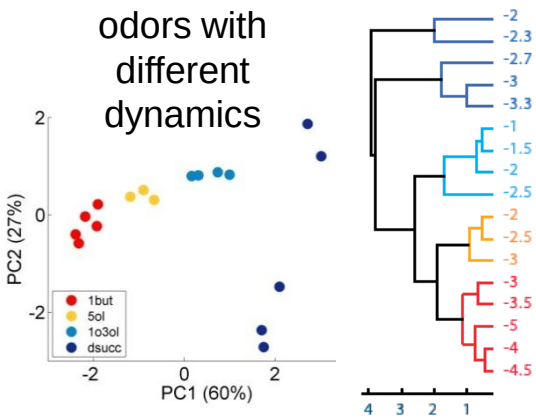


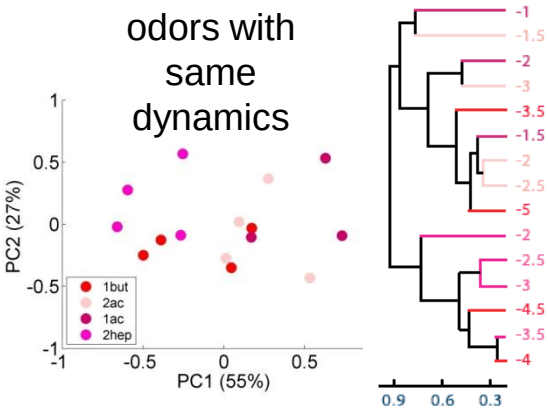
The nonlinear gain adapts.
The filter is <u>invariant</u>.

Implications for odor discrimination?

Contributions from a single ORN







Odors of different “speed” can be discriminated independently of their intensity from the response dynamics of a single ORN channel

Odors with similar “speed” cannot be discriminated using the information from a single ORN channel

Conclusions

One ORN responds with the same linear filter to many odorant. Filter remains the same even when ORN adapted to background odorant.

Large differences in ORN dynamics are often just the result of a convolution of large differences in stimulus dynamics with the neuron

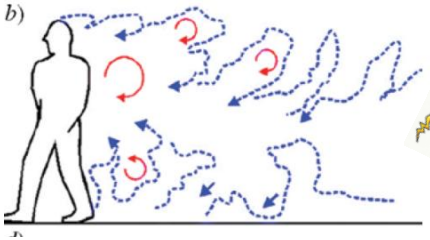
We observe small (~10 ms) delays in ORN response to different odorants.

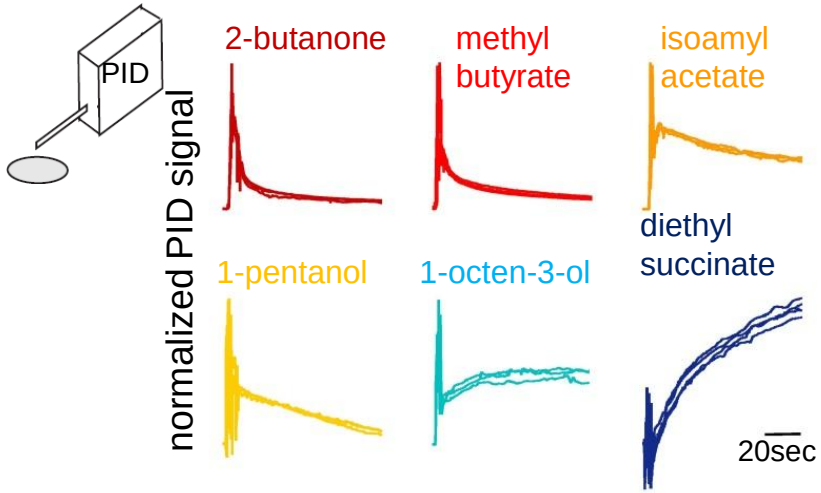
Is this relevant outside of the lab?

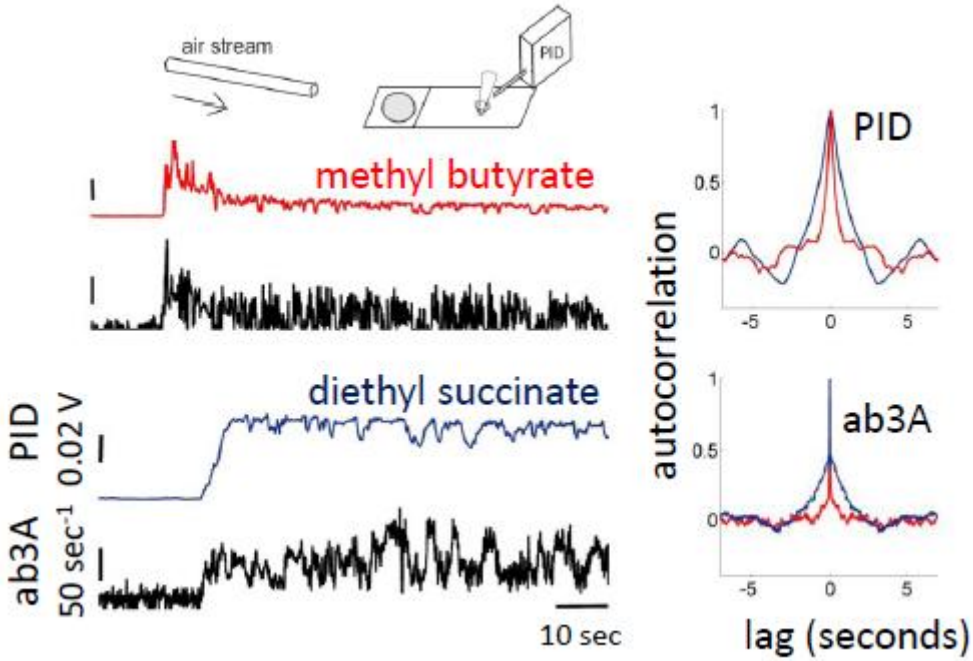
Odor-dependent time scales are detected close to surfaces

Head space

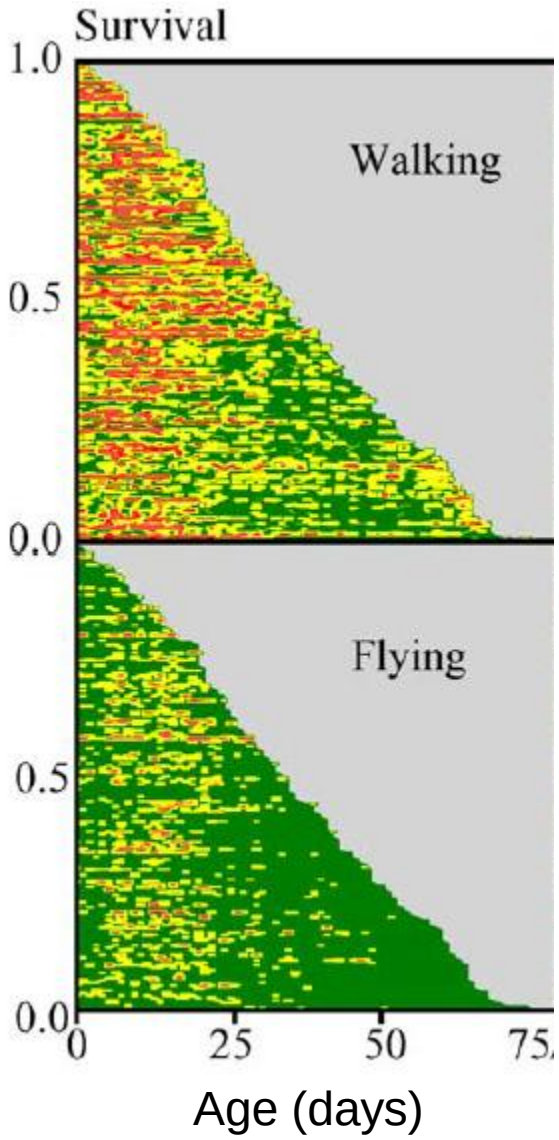
Fluctuating air stream







Living on surfaces



Fruit flies spend a lot of time on surfaces

2 h period recorded each day at 10 min intervals from 1000 to 1200 h

Carey JR et al, 2006

Conclusions

One ORN responds with the same linear filter to many odorant. Filter remains the same even when ORN adapted to background odorant.

Large differences in ORN dynamics are often just the result of a convolution of large differences in stimulus dynamics with the neuron

We observe small (~10 ms) delays in ORN response to different odorants.

Two worlds of olfaction:

- away from surfaces, transport is linear and stimulus dynamics is mostly invariant with respect to identity.

- Near surfaces, nonlinear interactions destroy time coherence between compounds

- **Question:** What happens to mixtures signals near surfaces? Is identity of signal compromised by surfaces?

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physico-chemical properties of odors determine odor “speed”