Stimulus dynamics and odor sensing

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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. 
Architecture of the olfactory periphery

1 receptor ~ 1 neuron ~ 1 glomerulus

Hallem, Trends in Genetics 2004
Measurements

Bacterial chemotaxis

Tumble

Run

Nature 2004

Insect olfaction

Carlson 1996

Shanbhag et al. 1999

10 µm

100 µm

1 µm

Hallem, Carlson (2004)
The combinatorial aspect

<table>
<thead>
<tr>
<th>ORNs</th>
<th>glomeruli</th>
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<tbody>
<tr>
<td>ammonium hydroxide</td>
<td>[Image of glomeruli]</td>
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<td>putrefic acid</td>
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<td>cinnamic acid</td>
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<td>dimethyl sulfoxide</td>
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Hallem, Cell 2006

Wang, Cell 2003
The temporal aspect

ORNs

Projection Neurons

same odor

receptors

Hallem, Cell 2006

See also Nagel and Wilson
Nature Neuro 2011

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

valve

main air

9cm 1.5cm

PID

single-unit recordings
stimulus dynamics…

\[ \tau \sim 3\text{ms to 1sec} \]

…depends on odor identity
stimulus dynamics…

\[ \tau \sim 3\text{ms to 1sec} \]

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

Surface interactions

\[
\partial_t c = \left(1 - F\right)c + Fc_0 - 2w
\]

\[
\partial_t q = k_a c (1-q) - k_d q
\]

Assume interactions are fast

\[
\left(1 + \frac{2w}{rK_d}\right) \partial_t c = \left(1 + \frac{c}{K_d}\right) c + c_0
\]
stimulus dynamics depend on odor identity and concentration

\[ \text{normalized PID signal} \]

- "fast odor": methyl butyrate
- "slow odor": 1-octen-3-ol
How do ORN response **dynamics** depend on the intensity of a “**fast**” odorant?
Dependence on odor concentration

- Dependence on odor concentration
- Independent concentration
- Dependent concentration

- Peak response (Hz)
- Degree of adaptation
- Normalized responses

- concentration dependent
- concentration independent
The response dynamics of individual ORN exhibit invariance with respect to odor concentration.
What if there is a background?

![Diagram showing odor concentration over time with background on and off intervals]

- 1 min
- 500 ms puffs
- Background on
- Background off
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

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

\begin{align*}
\mathcal{N}() & \quad k(t) \\
\text{valve to odor} & \quad \text{NR } 0.06 \\
\text{PID} & \quad 0 \\
\text{ORN} & \quad 0
\end{align*}
response function to slow and fast odors

methyl butyrate

1-octen-3-ol

delivery system

ab3A response
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.

**fast excitatory + slow inhibitor**

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

**slow excitatory + fast inhibitor**

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

Simulation with LN-Poisson cascade using ab3A LN model

Su, Martelli et al. PNAS 2011
How does the physiological response depend on odor identity?
Time [s]

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
How does adaptation affect the response function?
Compare ORN response at the beginning and end of the flickering stimulus.

The nonlinear gain adapts. The filter is invariant.
Implications for odor discrimination?
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

- 2-butanol
- methyl butyrate
- isoamyl acetate

Fluctuating air stream

- 1-pentanol
- 1-octen-3-ol
- diethyl succinate

Normalized PID signal

- PID
- methyl butyrate
- diethyl succinate

Autocorrelation

- ab3A
- PID

Lag (seconds)

10 sec

20 sec
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
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**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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• Michael Sneddon
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• Roger Alexander

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• Chih-Ying Su
• Heungwon Park
• John Carlson
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physico-chemical properties of odors
determine odor “speed”

\[ r = -0.45 \]