Spike-Frequency Adaptation Separates Transient Communication Signals from Background Oscillations

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Theory: Spike-frequency adaptation

- Phenomenon
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- Mechanisms
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- General model
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- Communication signals in weakly electric fish
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- Recordings of electroreceptor afferents
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Experiment: Weakly electric fish
- Communication signals in weakly electric fish
- Recordings of electroreceptor afferents
- Model predictions
A Universal Model for Spike-Frequency Adaptation

Phenomenon Spike-Frequency Adaptation

Plot showing the voltage (V [mV]) over time (t [ms]). The stimulus is shown as a horizontal line at the bottom of the plot.
Phenomenon Spike-Frequency Adaptation

- **Onset response** $f_0$
- **Steady-state response** $f_\infty$

Graph showing the change in frequency $f$ and voltage $V$ over time $t$. The onset response $f_0$ shows an initial increase followed by a gradual decrease, while the steady-state response $f_\infty$ remains relatively constant.
Mechanism: Encoder Adaptation

- M-type currents
- AHP-currents
- Slow recovery from inactivation

Input Current $I$

Firing Frequency $f(t)$

$g(J)$

$I-A$

subtractive
 Ionic currents over the cell membrane are parallel

⇒ Adaptation currents $A$ act **subtractively** on input current $I$:

$$I - A$$
M-type Currents

\[ I_M = \bar{g}_M a(V - E_K) \]

\[ \tau_a \dot{a} = a_\infty(V) - a \]
M-type Currents

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General Phenomenological Model

Biophysics of slow ionic currents $\Rightarrow$ model for firing frequency:

$$f(t) = f_0(I)$$
$f(t)$  firing frequency

$f_0(I)$  onset $f$-$I$-curve

$f_\infty(I)$  steady-state $f$-$I$-curve

$A$  adaptation current

$I_{th}$  threshold of $f_0$
General Phenomenological Model

Biophysics of slow ionic currents ⇒ model for firing frequency:

\[ f(t) = f_0(I - A) \]
$f(t)$ firing frequency

$f_0(I)$ onset $f$-I-curve

$f_∞(I)$ steady-state $f$-I-curve

$A$ adaptation current

$I_{th}$ threshold of $f_0$
General Phenomenological Model

Biophysics of slow ionic currents $\Rightarrow$ model for firing frequency:

$$f(t) = f_0(I - A)$$

$$\tau \dot{A} = A_\infty(f) - A$$
$f(t)$  firing frequency

$f_0(I)$  onset $f$-$I$-curve

$f_\infty(I)$  steady-state $f$-$I$-curve

$A$  adaptation current

$I_{th}$  threshold of $f_0$

$\tau$  adaptation time-constant
General Phenomenological Model

Biophysics of slow ionic currents \( \Rightarrow \) model for firing frequency:

\[
\begin{align*}
  f(t) & = f_0(I - A) \\
  \tau \dot{A} & = f_\infty^{-1}(f) - f_0^{-1}(f) - A
\end{align*}
\]
$f(t)$ firing frequency

$f_0(I)$ onset $f$-$I$-curve

$f_\infty(I)$ steady-state $f$-$I$-curve

$A$ adaptation current

$I_{th}$ threshold of $f_0$

$\tau$ adaptation time-constant
How does it work?

\[ f(t) = f_0(I) \]

\[ A = 0 \]
How does it work?

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How does it work?

\[ f(t) = f_0(I - A) \]

\[ \tau \dot{A} = f_\infty^{-1}(f) - f_0^{-1}(f) - A \]
Highpass Filter

Linearized $f$-$I$ curves $\rightarrow$ Linear adaptation $\rightarrow$ Transfer function $H_f(\omega)$

slopes of onset and steady-state $f$-$I$ curve: $f'_0$ and $f'_\infty$

effective time constant of adaptation: $\tau_{\text{eff}} \approx \tau_{f'_\infty} / f'_0$
Highpass Filter

Linearized $f$-$I$ curves $\rightarrow$ Linear adaptation $\rightarrow$ Transfer function $H_f(\omega)$

Slopes of onset and steady-state $f$-$I$ curve: $f'_0$ and $f'_\infty$

Effective time constant of adaptation: $\tau_{\text{eff}} \approx \frac{f'_\infty}{f'_0}$

$\Rightarrow$ Response depends on stimulus frequency

$\Rightarrow$ Timescale separation by cutoff frequency $\omega_{\text{cutoff}} \tau_{\text{eff}} \approx 1$
Weakly Electric Fish

Weakly Electric Fish (*Apteronotus leptorhynchus*)

Electric Organ Discharge (EOD)

600–1100 Hz
Weakly Electric Fish (*Apteronotus leptorhynchos*)

Electric Organ Discharge (EOD)

- Frequency: 600–1100 Hz
- Function: Prey detection
Weakly Electric Fish (*Apteronotus leptorhynchus*)

- Electric Organ Discharge (EOD)
- 600–1100 Hz
- Prey detection
- Communication
Communication I: Two Fish

Fish 1: EOD frequency $f_1$
Fish 2: EOD frequency $f_2$
Communication I: Two Fish

Fish 1: EOD frequency $f_1$
Fish 2: EOD frequency $f_2$

$\Rightarrow$ Beat with frequency $\Delta f = f_2 - f_1$
Communication I: Two Fish

Fish 1: EOD frequency \( f_1 \)
Fish 2: EOD frequency \( f_2 \)

\[ \Rightarrow \text{Beat with frequency } \Delta f = f_2 - f_1 \]

Male – Male

\[ |\Delta f| < 30 \text{ Hz} \]
Communication II: Small Chirps

Agonistic signals emitted during male – male interaction ($\Delta f < 30$ Hz)
Communication II: Small Chirps

short (14 ms) increase in EOD frequency (30–150 Hz)
Communication II: Small Chirps

short (14 ms) increase in EOD frequency (30–150 Hz)
Communication II: Small Chirps

EOD Fish 1 (male)
Communication II: Small Chirps

EOD Fish 1 (male) + EOD Fish 2 (male)

Chirp
Communication II: Small Chirps

EOD Fish 1 (male) + EOD Fish 2 (male)
Communication II: Small Chirps

EOD Fish 1 (male) + EOD Fish 2 (male) = EOD Amplitude Modulation Fish 1

- Chirp
- Beat 5 Hz
- Time [ms]
- Amplitude [mV/cm]
Communication II: Small Chirps

\[ \Delta f = 5 \text{ Hz} \]
Two stimulus timescales: (slow) beat and fast chirp.
Communication II: Small Chirps

$\Delta f = 30 \text{ Hz}$

$\Delta f = 10 \text{ Hz}$

$\Delta f = 5 \text{ Hz}$

⇒ Two stimulus timescales: (slow) beat and fast chirp.
In vivo recording of electroreceptor afferents (P-units)

\[ \Delta f = 10 \text{ Hz} \]
Response

In vivo recording of electroreceptor afferents (P-units)

Δf = 10 Hz
Spike-Frequency Adaptation!

Stimulus $I$

Firing Frequency [Hz]

Time [ms]

$f_0(I)$

$f_\infty(I)$
Spike-Frequency Adaptation!

\[ \tau_{\text{eff}} = 5.5 \text{ ms} \]

**Firing Frequency [Hz]**

**Stimulus** \( I \)

**Firing Frequency** \( f_0(I) \)

**Firing Frequency** \( f_{\infty}(I) \)
$F-I$ Curves

- **Baseline**
- **Steady-state $f_\infty(I)$**
- **Onset $f_0(I)$**

<table>
<thead>
<tr>
<th>EOD Amplitude $I$ [mV/cm]</th>
<th>Firing Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>82</td>
</tr>
<tr>
<td>384</td>
<td>62</td>
</tr>
<tr>
<td>267</td>
<td>42</td>
</tr>
<tr>
<td>149</td>
<td>8</td>
</tr>
<tr>
<td>108</td>
<td>8</td>
</tr>
</tbody>
</table>

EOD Amplitude $I$ [mV/cm] ranges from 1.8 to 3.0.
Firing Frequency [Hz] vs. EOD Amplitude $I$ [mV/cm]

- **Baseline**
- **Steady-state $f_\infty(I)$**
- **Onset $f_0(I)$**

$F$-$I$ Curves
$F-I$ Curves $\Rightarrow f(t) = f_0(I - A)$

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**Graph:**

- **Y-axis:** Firing Frequency [Hz]
- **X-axis:** EOD Amplitude $I$ [mV/cm]

- Three curves:
  - **Baseline**: Blue line
  - **Steady-state $f_\infty(I)$**: Red line
  - **Onset $f_0(I)$**: Green line

---

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<tr>
<th>EOD Amplitude $I$ [mV/cm]</th>
<th>Firing Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>(~82)</td>
</tr>
<tr>
<td>2</td>
<td>(~62)</td>
</tr>
<tr>
<td>2.2</td>
<td>(~42)</td>
</tr>
<tr>
<td>2.4</td>
<td>(~221)</td>
</tr>
<tr>
<td>2.6</td>
<td>(~8)</td>
</tr>
<tr>
<td>2.8</td>
<td>(~1000)</td>
</tr>
<tr>
<td>3</td>
<td>(~1000)</td>
</tr>
</tbody>
</table>
Model Prediction

\[ \Delta f = 5 \text{ Hz} \]
Δf = 5 Hz
\( \Delta f = 5 \text{ Hz} \)
$\Delta f = 30 \text{ Hz}$

Model Prediction

[Graph showing firing frequency and amplitude over time with response and model data indicated]
Highpass Filter of Adaptation

Linear $f$-$I$ curves $\rightarrow$ Linear adaptation: $\tau_{\text{eff}} \approx 7$ ms, $f'_0/f'_\infty \approx 6$
Highpass Filter of Adaptation

Linear $f$-$I$ curves $\rightarrow$ Linear adaptation: $\tau_{\text{eff}} \approx 7 \text{ ms}$, $f_0'/f'_\infty \approx 6$

![Graph showing the gain $|H_f|/f_\infty$ vs. stimulus frequency [Hz].](attachment:graph.png)

- $f_{\text{cutoff}}$ indicates the frequency at which the gain starts to increase.
- The graph shows a transition from linear to non-linear behavior as the stimulus frequency increases beyond $f_{\text{cutoff}}$. 
Highpass Filter of Adaptation

Linear $f$-$I$ curves $\rightarrow$ Linear adaptation: $\tau_{\text{eff}} \approx 7$ ms, $f_0'/f'_\infty \approx 6$

$\Rightarrow$ The high-pass filter’s cutoff frequency separates slow beats from fast chirps.
Summary

Theory: Spike-frequency adaptation

- Encoder adaptation: slow ionic currents.
Summary

**Theory**: Spike-frequency adaptation

- **Encoder adaptation**: slow ionic currents.
- **Shift of the neuron’s $f-I$ curve.**
Summary

Theory: Spike-frequency adaptation

- Encoder adaptation: slow ionic currents.
- Shift of the neuron’s $f-I$ curve.
- Highpass filter $\Rightarrow$ timescale separation.
Summary

**Theory**: Spike-frequency adaptation

- Encoder adaptation: slow ionic currents.
- Shift of the neuron’s $f-I$ curve.
- Highpass filter $\implies$ timescale separation.

**Experiment**: Weakly electric fish

- Slow beats and fast chirps.
Summary

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- Encoder adaptation: slow ionic currents.
- Shift of the neuron’s $f$-$I$ curve.
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Experiment: Weakly electric fish

- Slow beats and fast chirps.
- Firing frequency response of electoreceptor afferents to chirps is enhanced.
Summary

Theory: Spike-frequency adaptation
- Encoder adaptation: slow ionic currents.
- Shift of the neuron’s $f-I$ curve.
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Experiment: Weakly electric fish
- Slow beats and fast chirps.
- Firing frequency response of electroreceptor afferents to chirps is enhanced.
- Data can be explained by spike-frequency adaptation: Timescale separation by highpass filter.
Summary

Theory: Spike-frequency adaptation

- Encoder adaptation: slow ionic currents.
- Shift of the neuron’s $f-I$ curve.
- Highpass filter → timescale separation.

Experiment: Weakly electric fish

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- Firing frequency response of electroreceptor afferents to chirps is enhanced.
- Data can be explained by spike-frequency adaptation: Timescale separation by highpass filter.
Response Gain

Firing frequency difference during chirp divided by difference during beat

![Graph showing response gain vs. beat frequency](graph.png)

- $n = 505$
- $n = 251$
- $n = 73$
- $n = 247$
- $n = 60$
Behavior: System Output

![Graph showing chirp probability against Beat Frequency (Δf) [Hz].](image)

Similar reduction of electroreceptor response and behavior with increasing beat frequency.