Adaptation bei der Verarbeitung von Sinnesreizen: Kodierung von Kommunikationssignalen bei schwach Elektrischen Fischen

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Part I: How small chirps are encoded by electroreceptors

- Weakly electric fish
- Communication I&II: Slow beats and small chirps
- Spike-frequency response
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Theory: Spike-frequency adaptation
- Biophysical mechanisms
- General model
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**Theory**: Spike-frequency adaptation

- Biophysical mechanisms
- General model

- High-pass filter due to spike-frequency adaptation
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- General model

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Part II: A synchronization-desynchronization code
- Communication III: Fast beats and large chirps
- Desynchronization
- Synchronization
Part I

How Small Chirps are Encoded by Electroreceptors

Weakly Electric Fish \textit{(Apteronotus leptorhynchos)}

Electric Organ Discharge (EOD)

600–1100 Hz
Weakly Electric Fish (Apteronotus leptorhynchos)

- Electric Organ Discharge (EOD)
- mV/cm
- Time [ms]

600–1100 Hz

- Prey detection
Weakly Electric Fish \textit{(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 $f_2$

$\Rightarrow$ Beat with frequency $\Delta f = f_2 - f_1$

Male – Male $|\Delta f| < 30$ Hz

Male – Female $|\Delta f| > 60$ Hz
Mostly emitted during male – male interaction ($\Delta f < 30 \text{ Hz}$)
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)

Chirp Beat 5 Hz

Amplitude [mV/cm]

Beat 5 Hz

Chirp

Time [ms]

EOD Amplitude Modulation Fish 1
Communication II: Small Chirps

EOD Fish 1 (male)

EOD Fish 2 (male)

EOD Amplitude Modulation Fish 1

Amplitude [mV/cm]

0
0.5
1

Beat 5 Hz

Time [ms]

0
100
200

Chirp

ChirpBeat 5 Hz

Amplitude \[\text{mV/cm} \]
Communication II: Small Chirps

$\Delta f = 5 \text{ Hz}$
⇒ Two stimulus timescales: (slow) beat and fast chirp.
⇒ Two stimulus timescales: (slow) beat and fast chirp.
Electroreceptor Recordings: Setup
Spike-Frequency Response

In vivo recording of electroreceptor afferents (P-units)

$\Delta f = 10 \text{ Hz}$
Spike-Frequency Response

In vivo recording of electroreceptor afferents (P-units)

$\Delta f = 10 \text{ Hz}$
Theory:
A Universal Model for Spike-Frequency Adaptation

Phenomenon Spike-Frequency Adaptation

[Graph showing a spike train response to a stimulus over time (ms) and voltage (mV)].

- **Spike**: A burst of action potentials in response to a stimulus.

**Axes**:
- **Y-axis**: Voltage (V) in mV.
- **X-axis**: Time (t) in ms from -50 to 300.
Phenomenon Spike-Frequency Adaptation

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

Graph showing a change in frequency over time with voltage and stimulus levels.
Onset & Steady-State $f-I$ Curve

- $I = 52$ dB
- $I = 63$ dB
- $I = 79$ dB
Onset & Steady-State $f-I$ Curve

$I = 52\,\text{dB}$

$I = 63\,\text{dB}$

$I = 79\,\text{dB}$

Onset

$f_0(I)$

$f_\infty(I)$

steady-state
Mechanism: Encoder Adaptation

- M-type currents
- AHP-currents
- Slow inactivation of Na currents

\[ I-A \]
\[ g(J) \]

Input Current \( I \)

Firing Frequency \( f(t) \)
M-type Currents
M-type Currents

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

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

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

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

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

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

\[ I_M = \tilde{g}_M a (V - E_K) \]
\[ \tau_0 \dot{a} = a_\infty(V) - a \]
M-type Currents

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

\[ \tau a \dot{a} = a_\infty (V) - a \]

\[ \Rightarrow \quad A = \langle I_M \rangle \]

\[ \tau \dot{A} = A_\infty (f) - A \]

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![Graph of M-type Currents](image-url)

- **f_0(I)**
- **f_\infty(I)**
- **\( \tau_{\text{eff}} \)**
- **Time average!**

**Time axis:**
- \(-50\) to 300 ms

**Current density axis:**
- 0 to 120 \( \mu \text{A/cm}^2 \)
Adaptation currents ($I_M$, $I_{AHP}$, ...) are ionic currents.

Ionic currents flow in parallel over the cell membrane

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

$$I - A$$
Spike Generator and $f$-$I$ Curve

Spike frequency $f = f_0(I)$

Input current $I$ [μA/cm²]

Spike frequency $f$ [Hz]
General Phenomenological Model

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

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

Spike generator

J. Benda & A. Herz (2003), *Neural Computation* 15, 2523–2564
General Phenomenological Model

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

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

**Subtractiveness**

![Graph showing spike frequency $f(t)$ as a function of input current $I$. The graph includes curves for $f_0(I)$ and $f_0(I - A)$, with labels for thresholds and averaged adaptation currents.]

- $f(t)$: spike frequency
- $f_0(I)$: onset $f-I$ curve
- $I_{th}$: threshold of $f_0$
- $A$: averaged adaptation current

J. Benda & A. Herz (2003), *Neural Computation* 15, 2523–2564
General Phenomenological Model

Biophysics of slow ionic currents ⇒ model for spike frequency:

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

\[ \tau \dot{A} = A_\infty(f) - A \]

Adaptation dynamics

- \(f(t)\) spike frequency
- \(f_0(I)\) onset \(f\)-\(I\) curve
- \(I_{th}\) threshold of \(f_0\)
- \(A\) averaged adaptation current
- \(\tau\) adaptation time-constant

General Phenomenological Model

Biophysics of slow ionic currents ⇒ model for spike frequency:

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

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

Steady-state

- \( f(t) \): spike frequency
- \( f_0(I) \): onset \( f-I \) curve
- \( I_{th} \): threshold of \( f_0 \)
- \( A \): averaged adaptation current
- \( \tau \): adaptation time-constant
- \( f_\infty(I) \): steady-state \( f-I \) curve

How does it work?

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

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

\[ A = 0 \]

\[ f(t) = f_0(I) \]
How does it work?

\[ A = 0 \]

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

\[ \tau \dot{A} = f_\infty^{-1}(f) - f_0^{-1}(f) - A \]
How does it work?

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

\[ \tau \dot{A} = f^{-1}_\infty(f) - f^{-1}_0(f) - A \]
How does it work?

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How does it work?

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

\[ \tau \dot{A} = f_\infty^{-1}(f) - f_0^{-1}(f) - A \]
Back to Weakly Electric Fisch & Small Chirps

In vivo recording of electroreceptor afferents (P-units)

$\Delta f = 10\text{ Hz}$
Spike-Frequency Adaptation!
Spike-Frequency Adaptation!

Spike frequency [Hz]

$\tau_{\text{eff}} = 5.5 \text{ ms}$

$f_0(I)$

$f_\infty(I)$

Stimulus $I$
$F-I$ Curves

Spike frequency [Hz] vs. EOD Amplitude $I$ [mV/cm].

- **Baseline**
- **steady-state $f_\infty(I)$**
- **onset $f_0(I)$**
$F-I$ Curves

Spike frequency [Hz] vs. EOD Amplitude $I$ [mV/cm].

- **Baseline**
- **Steady-state** $f_\infty(I)$
- **Onset** $f_0(I)$
\[ F-I \text{ Curves} \Rightarrow f(t) = f_0(I - A) \]
$\Delta f = 5 \text{ Hz}$
Model Prediction

$\Delta f = 5$ Hz

- **Spike frequency**
  - 1000
  - 800
  - 600
  - 400
  - 200
  - 0

- **Amplitude**
  - 2.8
  - 2.4
  - 2
  - 1

- **Time [ms]**
  - -200
  - -100
  - 0
  - 100
  - 200

- **Response**
- **Model**
- **Data**

**Stimulus**

Data and model comparison for spike frequency and amplitude over time.
Model Prediction

$\Delta f = 5$ Hz

![Graph showing spike frequency and amplitude over time for model prediction with data and model responses. The graph has axes labeled 'time [ms]' on the x-axis, 'Spike frequency' on the y-axis, and 'Amplitude' on the opposite y-axis. The graph compares model and data responses with a stimulus waveform depicted in the bottom half.]
Model Prediction

\[ \Delta f = 30 \text{ Hz} \]
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 gain $|H_f|/f_\infty$ vs. stimulus frequency [Hz]. The graph shows a curve that rises from approximately 1 to 6 as the frequency increases from 1 to 100 Hz. There is a horizontal line at $f'_0/f'_\infty = 6$ and a vertical line at $f'_\text{cutoff}$, indicating the cutoff frequency.]
Highpass Filter of Adaptation

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

![Graph showing the gain $|H_f|/f'_{\infty}$ versus stimulus frequency in Hz, with a cut-off frequency $f'_{\text{cutoff}}$.](chart.png)
Highpass Filter of Adaptation

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

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

Part II

A Synchronization-Desynchronization Code for Natural Communication Signals

Slow Beat Modulates Firing Rate

In vivo recordings of electroreceptor afferents (P-units)

Beat $\Delta f = 20$ Hz
Fast Beat Synchronizes Electroreceptors

*In vivo* recordings of electroreceptor afferents (P-units)

Beat $\Delta f = 100 \text{ Hz}$
Fast Beat Synchronizes Electroreceptors

*In vivo* recordings of electroreceptor afferents (P-units)

Beat $\Delta f = 100$ Hz
**Fast Beat Synchronizes Electroreceptors**

*In vivo* recordings of electroreceptor afferents (P-units)

Beat $\Delta f = 100$ Hz
Two Social Contexts

**Male – female** interaction

- Fast beat (> 60 Hz)
- Synchronous response: spikes lock to stimulus on \( \approx 1 \text{ ms} \) timescale
Two Social Contexts

**Male – female** interaction

- Fast beat (> 60 Hz)
- Synchronous response: spikes lock to stimulus on ≈ 1 ms timescale

**Male – male** interaction

- Slow beat (< 30 Hz)
- Asynchronous response: modulation of firing rate
Communication III: Large Chirps

Signals emitted during male – female interaction ($\Delta f > 60$ Hz)

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Time [ms]</th>
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<td>50</td>
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Amplitude [mV/cm]

-0.1

Frequency [Hz]

800

1200

1600

2000

500 Hz

18 ms
Communication III: Large Chirps

EOD Female

EOD Male

Chirp
Communication III: Large Chirps

EOD Female

EOD Male

Chirp

EOD Amplitude Modulation Female

Amplitude [mV/cm]

0 2 4 6

-30 -20 -10 0 10 20 30

Time [ms]

Beat 130 Hz

Chirp

Beat 130 Hz

Chirp
Single Unit Response to Large Chirps

*In vivo* recordings of electroreceptor afferents (P-units)

Beat $\Delta f = 100$ Hz
Large Chirps Desynchronize Response

*In vivo* recordings of electroreceptor afferents (P-units)

Beat $\Delta f = 100$ Hz

Chirp 24 ms 600 Hz
Large Chirps Desynchronize Response

In vivo recordings of electroreceptor afferents (P-units)

Beat $\Delta f = 100$ Hz
Large Chirps Desynchronize Response

*In vivo* recordings of electroreceptor afferents (P-units)

Beat $\Delta f = 180$ Hz
Synchronization/desynchronization between $\Delta f \approx 50$ and 200 Hz
Large Chirps Desynchronize Response

Dual unit recordings

Correlation

Beat $\Delta f$ [Hz]

$n = 5$

- baseline
- beat
- chirp
Small Chirps Revisited

by Bill Ellis
Small Chirps Synchronize Response

*In vivo* recordings of electroreceptor afferents (P-units)

Beat $\Delta f = 10$ Hz

Firing rate modulation

Synchronization
Small Chirps Synchronize Response

*In vivo* recordings of electroreceptor afferents (P-units)

Beat $\Delta f = 5$ Hz
Summary

Male – female interaction:

- Fast beats ($\Delta f > 60$ Hz)
- Synchrony
- Large chirps desynchronize receptor population
Summary

**Male – female** interaction:
- Fast beats ($\Delta f > 60$ Hz)
  - Synchrony
- Large chirps
  - desynchronize receptor population

**Male – male** interaction:
- Slow beats ($\Delta f < 30$ Hz)
  - Firing rate modulation
- Small chirps
  - synchronize receptor population
Summary

Male – female interaction:
- Fast beats ($\Delta f > 60$ Hz)
  Synchrony
- Large chirps
desynchronize receptor population

Male – male interaction:
- Slow beats ($\Delta f < 30$ Hz)
  Firing rate modulation
- Small chirps
synchronize receptor population

Any change of the degree of synchrony could code a signal!
Summary

**Male – female** interaction:
- Fast beats ($\Delta f > 60$ Hz)
  - Synchrony
- Large chirps
desynchronize receptor population

**Male – male** interaction:
- Slow beats ($\Delta f < 30$ Hz)
  - Firing rate modulation
- Small chirps
  synchronize receptor population
- Spike-frequency adaptation
- High-pass filter