COMP 546

Lecture 23

Echolocation

Tues. April 11, 2017
How do bats navigate and catch prey in the dark?

• extra sensitive eyes?  extra sensitive skin?  (no)

• Lazzaro Spallanzani (late 1700's) showed the hearing was used  (cones and wax)

• Donald Griffin (1930's) measured ultrasound frequencies and found that bat emitted sounds in 12-200 kHz range.

  • humans hear up to 22 kHz only

  • 170 kHz ~ 2 mm (size of insects)
Echos and Time Delays

t = 0

$\Rightarrow$

$\Rightarrow$

$t = T$

echo heard when?

Use $d = vt$.

delay $\tau = \frac{2d}{v}$

measure $\tau$,
estimate $d$
Intensity and distance

Intensity $I^2$ reaching reflector \sim \frac{A}{d^2}
Intensity and distance

Intensity $I^2$ reaching reflector

$\sim \frac{A}{d^2}$

Intensity $I^2$ reaching ears

$\sim \frac{1}{d^2} \cdot \frac{A}{d^2}$

e.g. Exercise: Halving the distance leads to a SPL increase of how much (dB)?
ASIDE: Sound absorption in air
(previous example ignored this)

High frequency sounds are attenuated at a faster rate.
Also depends on humidity and temperature (not shown).
Bat concentrates its cry over a small range of directions (~40 deg) i.e. not over a uniform sphere. But still the emitted intensity falls off with distance squared.

We do this too, to some extent.
3 Computational Problems

• Detection (tree branches, prey e.g. insects)

• Localization (distance and direction)

• Recognition
Two types of bat cries

CF - constant frequency
FM - frequency modulated.
(only the fundamental frequency is shown)

How are these cries used to solve the computational problems?
CF (constant frequency)

Suppose a cry is 10 ms duration. (Often much longer than that.)

Distance per cry (many wavelengths!): $10 \text{ ms} \times 340 \text{ m/s} = 3.4 \text{ m}$
CF (constant frequency)

Suppose a cry is 10 ms duration. (Often much longer than that.)

Distance per cry (many wavelengths!): \[10 \text{ ms} \times 340 \text{ m/s} = 3.4 \text{ m}\]

If moth is less than 3.4/2 m away, then echo will overlap cry (not good).
Thus, CF only useful if the bat is far from the moth...
Main Advantage of CF: Lots of energy within a single auditory band makes the reflected echo easier to detect.

Analogy to vision: in presence of noise, you would have a better chance of seeing the sine pattern on left than on right.
Types of Masking

- “simultaneous”: cry (mask) overlaps echo (test)

- “forward”: cry (mask) occurs before echo (test)

Detection threshold of echo is elevated if gap is small.
Strategy: leave a large time gap between CF cries so that echo can be heard.

Time between cry and echo is a cue for **distance**.

Interaural level differences can be used for **direction** estimation.

In "detection" phase, cries (and gaps) would be long.

In "localization" phase, cries (and gaps) are shorter.
Recall: Simultaneous Masking experiment from lecture 21

\[ \omega_0 \quad \text{test} \]
\[ \omega_M \quad \text{mask} \]

Which interval contains the test tone?
Recall: “Critical bandwidth” $\Delta \omega$ for test frequency $\omega_0$.

The greater the difference between the mask and test frequency, the smaller is the masking effect. (A greater level difference between the mask and test is needed for masking to occur.)
Avoiding masking using a Doppler shift (1)

As the bat flies, it chases its emitted sound, causing the reflector to receive a slightly higher frequency. Recall critical band masking from last lecture.

One can show:

\[
W_{\text{observed by reflector}} = W_{\text{emit}} \left( \frac{V_{\text{sound}}}{V_{\text{sound}} - V_{\text{bat}}} \right)
\]
Avoiding masking using a Doppler shift (2)

As the bat flies into the reflected echoes, it observes a higher frequency. One can show:

\[ \frac{W_{\text{observed by bat}}}{W_{\text{emit}}} = \left( \frac{V_{\text{sound}}}{V_{\text{sound}} - V_{\text{bat}}} \right) \left( \frac{V_{\text{sound}} + V_{\text{bat}}}{V_{\text{sound}}} \right) \]
The expressions given above assume the reflector is not moving.

If the reflector is a flying moth, then the above model doesn't quite hold. One would need to take the motion (in depth) of the moth into account. (Details omitted.)
Acoustic fovea

The bat has an "acoustic fovea" on its basilar membrane. The bandwidth is very small at these frequencies.
The acoustic fovea reduces masking of the echo by the cry. How?

- Fovea frequency is fixed (hardwired).

- Echo has a higher frequency than the emitted cry. Bat modulates its emitted frequency e.g. based on its flight speed, to be at a frequency just below the fovea, so that the echo falls in the fovea.
Next... Recognition using CF

Moth wings beat at say 40 Hz (25 ms period)

Sound reflection only happens when moth wing is parallel to sound wave.

By using a cry of more than 100 ms, the bat can hear the wing beats and recognize the moth.
Advantages of CF:

Lots of energy within a single auditory band makes the reflected echo easier to detect

Disadvantages of CF:

The delay between the cry and echo cannot be computed reliably since the envelope is too large and ramps up

IID and ITD (last lecture) are limited to one band, so there is less information for inferring the arrival direction ($\phi$, $\theta$) of the echo
Frequency modulated (FM) cry

\[ I_{src}(t) = \sin(\omega(t) t) \]

where \( \omega(t) \) is a function of \( t \)
Example: linear chirp

\[ I_{\text{src}}(t) = \sin(\ \omega(t) \ t) \]

where \( \omega(t) = \omega_0 + \frac{\omega_1 - \omega_0}{2T} \ t \)
Example: linear chirp

\[ I_{src}(t) = \sin(\omega(t) t) \]

where \( \omega(t) = \omega_0 + \frac{\omega_1 - \omega_0}{2T} t \)

Phase \( \phi(t) \equiv \omega(t) t \)

\[ \frac{d}{dt} \phi(t) = \omega_0 + \frac{\omega_1 - \omega_0}{T} t \]

\[ = \begin{cases} 
\omega_0, & t = 0 \\
\omega_1, & t = T 
\end{cases} \]
localization (distance and direction) using FM

delay (echo-cry)

HRTF

$\omega$

t
Advantages of FM:

- echo is spread out over many bands, which allows estimation of source direction using HRTF cues

- duration within each band is short, which allows precise timing estimation

- don't need a big gap between cry and echo to avoid masking

Disadvantages of FM:

- weaker signal in each band
Typical Bat Spectrogram (cries only)

- **Constant frequency (CF)** detection & recognition (moth wing beats)
- **Frequency modulated (FM)** localization & recognition (discussed next)
Recognition using an impulse cry
(not physically possible for a bat)

\[ \delta(t) \quad \text{impulse} \quad \rightarrow \quad \text{object (e.g. moth)} \]

\[ m(t) \quad \text{impulse response} \]

\[ \omega \quad \text{Impulse cry} \quad \rightarrow \quad \text{Impulse echo} \quad \hat{m}(\omega) \]
Recognition using an FM cry

The peaks and notches of the echo are a signature of the shape of the moth.
Suppose the moth’s response function consist of two echos, separated by $\tau$.

$$m(t) = a \delta(t) + b \delta(t - \tau)$$

Then,

$$\hat{m}(\omega) = a + b e^{i \frac{2\pi}{\tau} \omega}$$

where $\omega$ is cycles/sec

$$\omega = \frac{1}{\tau}, \frac{2}{\tau}, \frac{3}{\tau}, ...$$

constructive interference

$$\omega = \frac{1}{2\tau}, \frac{3}{2\tau}, \frac{5}{2\tau}, ...$$

destructive interference
Cetaceans (dolphins, whales, ..) don't use CF or FM. Instead they use "clicks" namely $\sim \frac{1}{2}$ octave Gabors.

\[ V_{\text{water}} \approx 1500 \, \text{m/s} \]

\[ \lambda \approx \frac{V}{\omega} = \frac{1500}{75,000} \approx 0.02 \, \text{m} \]

width of a fish
Reflections of the front and back surfaces depend on fish shape and size.

For constructive interference, the width of fish must be half the peak wavelength because what matters is 'round trip' / 'aller-retour' distance.

<table>
<thead>
<tr>
<th>fish width</th>
<th>interference?</th>
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</thead>
<tbody>
<tr>
<td>$\frac{v}{4 \omega_0}$</td>
<td>destructive</td>
</tr>
<tr>
<td>$\frac{v}{2 \omega_0}$</td>
<td>constructive</td>
</tr>
<tr>
<td>$\frac{3v}{4 \omega_0}$</td>
<td>destructive</td>
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Can people echolocate? Yes, definitely. The blind use a cane to generate clicks and listen for echoes.

Some blind people echolocate by making clicks with their mouth.

See Daniel Kish videos e.g. https://www.youtube.com/watch?v=ob-P2a6Mrjs