BINAURAL HEARING and INTELLIGIBILITY in AUDITORY DISPLAYS

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1. Binaural hearing phenomena

2. Newly developed auditory displays that exploit spatial hearing for improving
   - speech intelligibility
   - alarm intelligibility

   in aviation applications
Physical characteristics of sound and perceived attributes

• Frequency (perceived pitch)
• Intensity (loudness)
• Spectral content (timbre)
• FIS, plus binaural differences (localization)
Physical characteristics of sound and perceived attributes

• **F**requency ➔ (perceived pitch)
• **I**ntensity ➔ (loudness)
• **S**pectral content ➔ (timbre)
• **FIS**, plus binaural differences ➔ (localization)

** All characteristics are important in the identification and discrimination of auditory signals and for speech intelligibility in communication contexts
Two important functions of the binaural hearing system

• Localization
  (lateral and 3-dimensional)

• Binaural release from masking:
  Echo suppression, room perception
Binaural hearing (localization; signal separation & detection):

forming spatial auditory events from acoustical (bottom-up) and psychological (top-down) inputs
Filtering of acoustic signal by pinnae, ear canal

Model of the binaural hearing system

Binaural hearing (localization; signal separation & detection)
Model of the binaural hearing system

- Filtering by pinnae, ear canal
- Filtering by inner ear; frequency-specific neuron firings
- Binaural hearing (localization; signal separation & detection)
- Acoustically-driven
- Psychologically-driven

Acoustic signal-driven

- Middle-ear filter
- Cochlea simulation
- Binaural processor
- Monaural processor
- Formation of the auditory event
- Non-auditory sensory information
- Cognition

Feedback connections
Filtering of acoustic signal by pinnae, ear canal

Filtering by inner ear; frequency-specific neuron firings

Physiological evaluation of interaural timing and level differences

Binaural hearing (localization; signal separation & detection)
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Filtering by inner ear; frequency-specific neuron firings

Physiological evaluation of interaural timing and level differences

Binaural hearing (localization; signal separation & detection)

Model of the binaural hearing system

Psychologically-driven

Multi-sensory information; cognition

Acoustically-driven

Filtering of acoustic signal by pinnae, ear canal.
Lateral localization of auditory images

“Duplex” theory of localization

- ILD (interaural level difference)
- ITD (interaural time difference)
Lateral spatial image shift

- **ILD** (interaural level difference) caused by head shadow of wavelengths > 1.5 kHz

![Graphs showing level difference for 6,000 Hz and 200 Hz frequencies across different directions of sound source.](image)
Lateral image shift

- ITD (interaural time difference)
Head-related transfer function cues (HRTFs) provide cues for front-back discrimination and elevation.

Basis of 3-D audio signal processing in auditory displays.
Vibration source (internal, external)

Ground, Structure response

Airborne sound

Walls, Windows, objects

Chairs, Tables, floor

Walls, Windows, plants

3-D audio display

Expectation
Inter-modal coordination
Identification
Experience-adaptation

Response:
qualitative assessment
Performance metric

Sound sources can be ‘felt’ and ‘seen’ as well as heard
Applications of spatial sound for improving intelligibility in auditory displays
Using binaural hearing advantage for separating multiple auditory “streams” (simultaneous sources)

Proposed 3-D audio communication system

- Each communication channel is spatially separated.
- User can use selective attention to switch between signals, as in normal hearing.
- Background noise reduced via on-the-ear, active noise cancellation headsets.
- Normal communication still possible without intercom
- * Improved intelligibility
- * Less fatigue
3-D communication system patented, developed for NASA-KSC
Speech Intelligibility advantage compared to one-ear listening

Azimuth of spatialized signal (mean of left & right sides)

Advantage (dB)

Full frequency bandwidth

Telephone bandwidth
Hearing loss for target users: 64 active commercial airline pilots

<table>
<thead>
<tr>
<th>Age Range</th>
<th>Question 1 (&quot;Told by a doctor&quot;)</th>
<th>Question 2 (&quot;Personally suspect...&quot;)</th>
<th>General Population</th>
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<tr>
<td>35-44</td>
<td>25%</td>
<td>30%</td>
<td>11%</td>
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<td>45-54</td>
<td>50%</td>
<td>60%</td>
<td>23%</td>
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<tr>
<td>55-64</td>
<td>75%</td>
<td>80%</td>
<td>30%</td>
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</table>
Audiogram data summary for 20 active commercial pilots (age range 35-64; not corrected for presbycusis)
Use of auditory icons (AI) and left-right spatialization for information redundancy, situational awareness of actions of crew (CRM) and haptic feedback substitution

“Page-through” & “switch” AIs for touch screen checklist

“Mechanical latch” AIs for actions corresponding to electrical, fuel, hydraulic systems

NASA ARC advanced cab simulator
Head up auditory display for TCAS

3-D audio alert

Visual field of view

CAPTAIN'S SCREEN  COMMON SCREEN  FIRST OFFICER'S SCREEN
Application of 3-D audio head-up display for Traffic Collision Avoidance System (TCAS II) investigated. Target acquisition times can decrease from 0.5 – 2.2 sec.
Mean target acquisition times (4.7 vs. 2.5 s) and standard deviations for first TCAS experiment. The 3-D audio cues were exaggerated in azimuth relative to the visual target, and no elevation cues were supplied.

Mean target acquisition times (2.63 vs. 2.13 s) and standard deviations for second TCAS experiment. The 3-D audio cues were not exaggerated, and there were three categories of elevation cues.
Head-up auditory display with head-up visual display
Application of 3-D audio head-up display for taxiway turnoff guidance
Reduction in taxi time:
Advantage of 3-D audio
Spatially-modulated auditory alerts
In an auditory display, how to insure that an alarm is audible?

-“Common sense” engineering approach: make the alarm *a lot louder* than the background noise for wide-area coverage

*Fire alarm and horn from ca. 1933*
In an auditory display, how to insure that an alarm is audible?

-ISO 7731 ("Danger signals for work places-Auditory danger signals") specifies signal to be $\geq 13$ dB re masked threshold in a 1/3 octave band (0.3-3.0 kHz)

-Recipe for “startle effect”, high overall SPLs, and potentially low performance in a high-stress environment
Current approach

-Improve detection of an alarm (signal) against ambient sound (noise) using signal processing techniques other than level increase

Requirement / Caveat

-Technique should apply to currently-used alarms (to avoid “relearning” semantic content of new auditory signals).

Technique

-Three methods addressed in patent application (pending) for accomplishing this.
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Alarm (basic stimulus)

737-300 alarm: Two successive square waves (preceding verbal “wind sheer” alert)

200 Hz 764 Hz

300 ms 300 ms
Summed L+R RMS levels equivalent for all stimuli; but jittered stimuli have +5 dB peaks re unjittered due to HRTF.
Results (1)

Headphone with jittered signal has 13.4 dB advantage over monaural loudspeaker (existing condition on aircraft), partly due to attenuation of noise by headphone.
Results (2)

Headphone with jittered signal has significant ($p < .000$) 7.8 dB advantage over headphone without jittered signal. No significant difference between 1.6 and 3.3 Hz modulation.
Conclusions

A new approach to designing alerts for auditory displays in high-stress interfaces: use of spatial modulation for improved detection.

Headphones + spatial modulation lower threshold by 13.4 dB.

Spatial modulation lowers threshold by 7.8 dB. 5 dB is due to HRTF interaural level difference if instantaneous (peak) level differences are assumed. This amount is reduced as a function of longer temporal integration periods. Remaining advantage is due to time varying interaural cross-correlation.
BINAURAL LOCALIZATION

+ THE "COCKTAIL PARTY" EFFECT

+ ACTIVE NOISE CANCELLATION

= Benefits: increased aviation safety & efficiency

• IMMEDIATE SITUATIONAL AWARENESS (WITH HEADS-UP ADVANTAGE)

• ALTERNATIVE or REDUNDANT DISPLAY for VISUALLY-ACQUIRED INFORMATION

• INTELLIGIBILITY IMPROVEMENT
  Binaural release from masking

• DISCRIMINATION and SELECTIVE ATTENTION IMPROVEMENT

HEARING CONSERVATION

ACTIVE NOISE CANCELLATION