Hearing Aid Ingredients to Enhance Effortless Hearing

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LISTENING IS HARD WORK …
We hear:

“The foo... is delicious”
“please sit here”
“I listen to it also”
“What is the date”
AUDITORY SCENE ANALYSIS – A MATTER OF OBJECT FORMATION (OR ORGANIZATION)

Information from both ears
Pitch
Temporal – onset/offset, modulation, duration
Context & content
THUS, AN ACCURATE AND COMPLETE INPUT IS IMPORTANT

Insufficient intensity

Hearing loss

Missing source
INPUT-RELATED DEMANDS AFFECT THE EASE OF ASA

Phonological information (multi-modal) → Auditory scene analysis

INPUT RELATED DEMANDS
Source – e.g., accented speech
Transmission – e.g., hearing aids, room acoustics
Listener – e.g., age, APD, HL
Message – e.g., familiarity
Context – e.g., visual, knowledge
EASE OF LANGUAGE UNDERSTANDING

EASE OF LANGUAGE UNDERSTANDING MODEL
RONNBERG (2008)

Phonological information (multi-modal) → Auditory scene analysis →

Does it match with phonological representation in LTM (automatic, implicit processing)?

Yes → Understand and Action

No → Go to explicit, top down processing

Source – e.g., accented speech
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THE EXPLICIT PROCESSING

The Problem Solving Loop

1. Identify the problem.
2. Explore information and create ideas.
3. Select the best idea.
4. Build and test the idea.
5. Evaluate the results.
Listening effort is the mental energy (or attention, perceived or otherwise) that a person puts into a communication situation.
THE GOODNESS OF THE SIGNAL AFFECTS THE AMOUNT OF EFFORT YOU PUT IN
INDIVIDUAL WORKING MEMORY AFFECTS UNDERSTANDING

Phonological information (multi-modal) → Auditory scene analysis

Does it match with phonological representation in LTM (automatic, implicit processing)?

Yes → Understand and Action

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Requires attention & effort

Source – e.g., accented speech
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Good working memory

Poor working memory

Requires attention & effort
A SIMPLIFIED EXPLANATION ON WORKING MEMORY

The retention of information in conscious awareness when the information is not present in the environment, … for its manipulation and use in guiding behavior (Postle, 2006, cited in Pichora-Fuller, 2016)
DIFFERENCES BETWEEN GOOD AND POOR WORKING MEMORIES

• Correlated with reading comprehension scores, SAT, speech in noise ability, and success with different signal processing methods

• People with poor WM
  • Acceptable performance when tasks are simple
  • Fails with more than one task or when tasks are more complicated
  • Greater need to minimize the input related demands
    • Needs to preserve the naturalness of the input
  • More distracted by multiple sources of stimuli
    • Needs a cleaner signal

• People with better WM
  • Acceptable performance even with more than one task or when tasks are complicated
  • Better able to tolerate distortion (temporal distortion, interference, noise) and “fill-in” gaps
  • Less distracted by multiple sources of stimuli
  • Faster processing speed
  • Will still fail when tasks are sufficiently complicated/demanding
SUMMARY: FACTORS AFFECTING UNDERSTANDING

• How good are the input sounds (Input-related demands)
  • Speaker characteristics
  • Listener characteristics – normal, HL, CAPD etc
  • Familiarity with topic/context
  • Room (listening) environments
  • Transmission characteristics (hearing aids, ALDs etc)

• Listeners’ working memory
  • Determines their capacity to understand

• Listeners’ motivation to understand (cost/value)
  • Determines their allocation of capacity
AGE-RELATED CHANGES – LOSS OF SYNAPTIC DENSITY

(Terry & Katzman, 2001)
AGE-RELATED CHANGES – LOSS OF BRAIN STRUCTURE & SYNCHRONY

• Aging decreases *cortical thickness* (Bilodeau-Mercure et al, 2015) using MRI studies.
  • Supratemporal cortex, bilateral ventral motor areas, left ventral premotor cortex and right supplementary motor area, sensorimotor cortex and left dorsal anterior insula (for speech)
• Frontal and temporal lobes are most affected (Raz, 2005)
  • Also seen in parietal (spatial processing), cerebellum and hippocampus from shrinkage of neurons
  • Length of myelinated fibers also decreases with age
• Neural responses are desynchronized (e.g., Clinard et al, 2013)
• Symmetry in P1-N1 recorded in the left/right temporal lobes increases (Bellis, 2000)
• Size of working memory decreases
THE INTENTION AND ATTENTION SYSTEMS

Cingulo-opercular intention system
- Bilateral dorsal cingulate
- Inferior frontal
- Anterior insula

Frontal-parietal attention system
- Inferior frontal sulcus/precentral sulcus
- Dorsolateral prefrontal cortex/middle frontal gyrus
- Intraparietal sulcus
- Inferior parietal lobules

Vaden et al, 2013
AGE RELATED CHANGES IN INTENTION AND ATTENTION SYSTEMS

Cingulo-opercular system
- Increases activity in noise
- Evaluates the need to signal attention system
- Maintains optimal performance over time

Frontal-parietal system
- Receives input from CO
- Attention control by increasing inhibitory action
- Increases activity with age

Decreased connectivity with age
- Decrease in inhibitory control
- Discounts the value to improve performance
LISTENING BECOMES MORE EFFORTFUL

• Loss of sensory input with age, loss of inhibitory control (from attention system), loss of input from intention system means the brain has to work harder to maintain same level of performance

• Posterior-Anterior shift with Aging (Davis, 2008)
  • Increased activity in prefrontal region

• Scaffolding theory of aging and cognition (Lustig, 2009) suggests compensation can be enhanced through training
EFFECT OF AGING ON LANGUAGE UNDERSTANDING

**Phonological information (multi-modal)**

**Auditory scene analysis**

Does it match with phonological representation in LTM (automatic, implicit processing)?

Yes

**Understand and Action**

No

**Go to explicit, top down processing**

Requires attention & effort

**Poor working memory**

Good working memory

Source – e.g., accented speech
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AGING, SENSORY LOSS & COGNITION

$N = 245$
- Y, M & O;
- Hearing, Vision, Touch & Cognition

$\text{SensProc\_global}$

$\text{COG\_global}$

$\text{Age}$

$r = -0.55$
$r = 0.75$
$r = -0.70$

(Humes et al, 2016)
COGNITIVE LOSS IS **CLOSELY TIED TO SENSORY LOSS**

The older the subject, the poorer the threshold sensitivity and temporal processing in hearing, touch and vision.

The poorer the sensory processing in hearing, touch and vision, the poorer the cognitive function.
A MORE SEVERE HEARING LOSS IS LINKED TO AN INCREASED RISK FOR DEMENTIA

- Lin et al (2011, Arch Neuro) reported incidence of dementia is higher in hearing impaired people than normal hearing people (adjusted for age, health etc)

Hazard ratio of dementia re: normal hearing (HR=1)
THE ADDED EFFECT OF HEARING LOSS ON LANGUAGE UNDERSTANDING IN THE ELDERLY

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- Requires attention & effort
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- Good working memory
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SUMMARY OF AGE-RELATED CHANGES

• Decrease in synaptic density and synchrony
• From top down - Cognitive decline
  • In fluid but not crystallized intelligence
  • Greater difficulty with memory encoding and retrieval
  • Less inhibitory control
• From bottom-up - Loss of sensory input
  • Retrograde degeneration
  • Poorer neural synchronization (temporal encoding)
  • Less integration of bilateral info - spatial processing
  • Less specificity in stimulation (from reorganization)
• Vulnerability to interference - difficulty segregating wanted from unwanted signals
• Decrease perceptual speed and reaction time
• More effortful listening
• Poorer speech recognition especially in difficult situations
Can hearing aids slow cognitive decline?
AMIEVA ET AL STUDY SHOWS HEARING AIDS ATTENUATE COGNITIVE DECLINE


(From Amieva et al, 2015)
Study Shows That Hearing Aids Improve Brain Function

Published on February 15, 2016
TO FURTHER IMPROVE LANGUAGE UNDERSTANDING IN ELDERLY INDIVIDUALS WITH A HEARING LOSS

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Poor working memory

Good working memory
REDUCING THE AMOUNT OF EFFORT - MAKING SOUNDS...

Cleaner

At a more comfortable level

More natural
A “BLINDER” FOR THE RIGHT MOMENT
EFFORTLESS HEARING DESIGN RATIONALE - MINIMIZE NEED FOR EXPLICIT PROCESSING

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Poor working memory
REQUIREMENTS FOR EFFORTLESS HEARING DESIGN

• A continuous process

• As a first step, the sounds that the listeners hear must be
  • Audible – to compensate for the loss of audibility from the hearing loss
  • Natural – so all the frequency and temporal cues (as well as inter-aural cues) are preserved for easy identification
  • Useful – so cognitive resources will not need to be spent on unimportant sounds
    • Getting rid of unwanted sounds (minimize distractions)
    • Enhancing wanted sounds – compensate for peripheral and central losses

• Personalization/Individualization
  • Physical ear (RECD)
  • Etiologies (conductive, sensory, neural, WM)
  • Preferences (comfort vs intelligibility), learning style
  • Environments
FUNCTIONAL REQUIREMENTS ON HEARING AIDS

CAPTURE
So you have everything at your disposal

PURIFY
So you don’t hear what you don’t need

PROCESS
So you hear what you need
CAPTURE WHAT YOU NEED

• A natural signal allows easier extraction of features for more accurate object formation
• Requires
  • Information from both ears – interaural time and intensity differences
  • Full spectrum of sounds
  • Temporal information – onset/offset, modulation, duration
• WITHOUT DISTORTION
SUMMARY OF BEYOND FEATURES THAT CAPTURE NATURAL NUANCES

• Bilateral amplification
  • To improve speech understanding in noise
  • Inter-ear compression to restore inter-aural cues
• Digital pinna to compensate front-to-back ratio in BTE/RIC aids
• Hearing aid microphone and receiver with broadest bandwidth and widest dynamic range
• Analog-to-digital converter
  • A high sampling rate (33 kHz)
  • A large number of bits (18 bits)
    • A high input limit (113 dB SPL)
    • A large linear input dynamic range (108 dB)
  • Four (4) ADC
• Audio streaming (in BEYOND)
• Provide ingredients for accurate Acoustic Scene Analysis
PURIFY – SO YOU DON’T HEAR WHAT YOU DON’T NEED

• Because unwanted sounds are distracting
• Because elderly individuals spend more effort to maintain performance
• A cleaner signal allows easier object formation
• Natural but undesirable inputs
  • Wind noise
  • Background noise
    • Directional microphones
    • Noise reduction algorithms
SUMMARY OF BEYOND FEATURES THAT PURIFY INCOMING SOUNDS

• SmartWind manager
  • ONLY commercial wind noise algorithm that:
    • Improves speech-to-wind noise ratio by 8 dB and reduces annoyance
    • Regardless of wind directions, monaural or bilateral fitting
    • Extends the satisfactory use of hearing aids from mainly indoors to both indoors and outdoors

• Multichannel fully adaptive directional microphone (HD Locator)
  • Improves speech in noise (SNR) ability by as much as 6 dB

• Inter-ear speech enhancer
  • Reduces listening effort in noise
So desirable speech features are more salient for object formation

- Individualized fitting
- Dual speed compression
- Sound class system
- Frequency transposition
HISTORICALLY, THE EMPHASIS ON COMPRESSION IS HOW LOUDNESS SHOULD BE RESTORED
… WITHOUT MUCH CONSIDERATION ON THE TEMPORAL ENVELOPE
SOME PEOPLE ARE ESPECIALLY DEPENDENT ON TEMPORAL ENVELOPE

- Low cognition
- Low contextual cues
- Elderly
- Severe hearing loss
WHAT CAN AFFECT TEMPORAL STRUCTURES?

Noise fills in the gap between speech segments and decreases modulation and envelope fidelity – input related.

Multichannel compression (especially fast acting WDRC) reduces peak to valley – output related.

Saturation distortion (peak clipping) or compression limiting at input or output stages – input/output related (True Input Technology).
EFFECT OF SPEED OF COMPRESSION (TIME CONSTANTS) ON TEMPORAL ENVELOPE

**STATIC INPUT-OUTPUT CURVE**

**ORIGINAL UNAMPLIFIED**

**FAST-ACTING COMPRESSION**

**SLOW-ACTING COMPRESSION**
LONG TIME CONSTANTS **LINEARIZE** A NONLINEAR HEARING AID
CONSEQUENCES OF USING ONLY FAST ACTING COMPRESSION

- Ensures audibility, but at the expense of
- Reduction of temporal envelope cue – could affect those with cognitive issues
- Lowered speech intelligibility when used with a high CR (> 3) (Plomp, 1988)
- Spectral smearing in a multichannel compression hearing aid, resulting in poorer speech intelligibility despite enhanced audibility (Bor et al, 2008; Souza et al, 2005)
- Ambient noise becomes more perceptible during pauses between speech
- Reduced signal-to-noise ratio in moderate levels of background noise
- Reduced inter-aural level differences between two hearing aids of a bilateral pair. This could make spatial awareness and localization more difficult
- More prevalent in compressors with more channels and a higher CR
CONSEQUENCES OF USING ONLY SLOW ACTING COMPRESSION

• Preserves short term changes within the waveform (temporal envelope)
• Preservation of signal-to-noise ratio in moderately noisy backgrounds (Neuman et al, 1998)
• Preservation of natural inter-aural level difference cues for spatial hearing
• Higher naturalness and better sound quality (e.g., Neuman et al, 1995, 1998; Hansen 2002).
• Better speech intelligibility for people with more than a moderate loss (Souza et al, 2005; Davies-Venn et al, 2009)
Some studies have suggested that people with good working memory should use fast-acting compression; while people with poor working memory should use slow acting compression.
### My Take on the Noted Link Between Speed of Compression and Cognitive Abilities

All people (good and poor WM) can use audibility cues; but only good WM can tolerate a loss of temporal cues (or poor WM rely more on temporal cues).

<table>
<thead>
<tr>
<th></th>
<th>Fast acting</th>
<th>Slow acting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good WM</td>
<td>Distortion – present, not bothered Audible cues - useful</td>
<td>Distortion – absent Audible cues - loss</td>
</tr>
<tr>
<td>Poor WM</td>
<td>Distortion – present, bothered Audible cues - useful</td>
<td>Distortion – absent Audible cues - loss</td>
</tr>
</tbody>
</table>
Thus a compressor that preserves the temporal cues while maximizing the audibility cues could be beneficial for people with good working memory AND people with poor working memory
THE VARIABLE SPEED COMPRESSOR IN THE BEYOND ACHIEVES THE BEST OF BOTH WORLDS
BENEFITS FROM VARIABLE SPEED COMPRESSION – CONSISTENT AUDIBILITY

![Graph showing the relationship between Unique (%) and Dream-M (%) for Phonemes, Consonants, and Vowels.](image1)

![Bar chart showing performance (%) for ORCA-NST with categories: Stops, Nasals, Fricatives, Approximants, and Lateral approximants.](image2)
MORAL OF THE (DUAL COMPRESSOR) STORY

Advanced technology may accommodate people of all cognitive backgrounds by providing all with the required information (audibility and temporal cues)

YES WE CAN
AUDIBILITY EXTENDER – FOR PEOPLE WITH UNAIDABLE/UNREACHABLE HIGH FREQUENCY HEARING LOSS

- True linear frequency transposition
  - Analyze spectrum
  - Find sound
  - Set target
  - Transpose sound
  - Filter sound
  - Overlay sound

- Preserves the important harmonic relationships (ratio) of the transposed sounds to the original sounds
USING A COGNITIVE MODEL TO **ENHANCE OUTCOME** OF FREQUENCY TRANSPOSITION

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- **Good working memory**
- **Poor working memory** Requires attention & effort

... and motivation!!
IMPROVING USE OF FREQUENCY LOWERING

Reducing the initial mismatch

Adapting to the transposed sounds
PRESERVE SOUND QUALITY - HARMONIC TRACKING

Spectrum computed from the last note of the three note sequence

Original  AE with tracking  AE w/o tracking  Sequence where the last note of harmonic tracking altered (T-NT)
Voiced speech sounds will be attenuated in the target region, unvoiced speech sounds will be transposed with max AE gain to increase salience of unvoiced speech sounds
MINIMIZING INITIAL MISMATCH – ADJUSTABLE OUTPUT FREQUENCY RANGE
WHY AN ADJUSTABLE OUTPUT FREQUENCY RANGE?

Not everyone who is a candidate for frequency lowering has a dead region.

Some candidates for frequency lowering have a dead region.
## INTERACTIONS BETWEEN BANDWIDTH AND POTENTIAL DISTORTION

<table>
<thead>
<tr>
<th></th>
<th>Aided without AE</th>
<th>AE with 3kHz bandwidth</th>
<th>AE with 10kHz bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Music</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no distortion</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
</tr>
<tr>
<td>with distortion</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
</tr>
<tr>
<td><strong>Speech</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no distortion</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
</tr>
<tr>
<td>with distortion</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
</tr>
<tr>
<td><strong>Birds</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no distortion</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
</tr>
<tr>
<td>with distortion</td>
<td>☀️</td>
<td>☀️</td>
<td>☀️</td>
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*Note: ☀️ indicates no distortion, ☀️ indicates with distortion.*
MINIMIZING INITIAL MISMATCH – HIGHER START FREQUENCY

Previous rule SF = 3k

BEYOND rule SF = 4K
MINIMIZING INITIAL MISMATCH - AE ACCLIMATIZATION
A COGNITION BASED AUDIBILITY EXTENDER PROTOCOL

Start → Small difference → Training/repeated use → Acclimate to AE gain → Increase difference → Reached target setting?

   YES → Stop

   NO → Start
ENHANCED AUDIBILITY EXTENDER

• EFFORTLESS HEARING through MINIMIZING MISMATCH

• Improved sound quality
  • Harmonic tracking
  • Speech detector

• Individualized settings for loss and cognition
  • Start frequency
  • Output frequency range

• Adaptation
  • AE acclimatization
  • Training
MORAL OF THE ENHANCED AE STORY

“The Boiling Frog story is often used as a metaphor for the inability of people to react to significant changes that occur gradually or to events which have become commonplace.”
CONCLUSIONS - EFFORTLESS HEARING

• **Effortless Hearing** design rationale
  • Maximizes potential speech understanding while minimizing wearer effort (in listening, use etc)
  • Minimizes the clinicians’ need to differentiate patients with good vs poor working memory so everyone utilizes the full potential provided by our hearing aids

• Key questions to ask - how do the hearing aids
  • Capture
  • Purify and
  • Process sounds while
  • Ensuring customized processing yet simplicity of use