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Hearing Smarter: How AI is Transforming Hearing Aids

Joshua M. Alexander, PhD, CCC-A

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Joshua M. Alexander, PhD CCC-A

Joshua Alexander, CCC-A, is an Associate Professor in the Department of Speech, Language, and Hearing Sciences at Purdue University, where he has recently been appointed the Innovation and Entrepreneurship Fellow for the College of Health and Human Sciences. He received his B.S., M.S., and Ph.D. in Audiology from the University of Wisconsin-Madison, where he also researched speech perception as a post-doctoral scientist. Additionally, he completed clinical and post-doctoral fellowships at Boys Town National Research Hospital in Omaha, Nebraska.

Dr. Alexander is dedicated to advancing speech understanding and reducing listening effort for hearing aid users. He has developed a sophisticated hearing aid simulator that replicates the features of commercial hearing aids. This tool has been instrumental in at least 14 peer-reviewed articles, 5 NIH grants, and the discovery of significant new knowledge, resulting in four U.S. patents.

Funding from NIH and hearing aid manufacturers have supported his research. He consulted on an NIH SBIR grant for Creare, LLC, which created the Tympan open-source audio processing platform. Initially conceived as an open-source hearing aid, this platform is now being expanded into a comprehensive audiological test suite, with Purdue serving as the primary test site.

Dr. Alexander is part of a team that recently opened the Accessible Precision Audiology Research Center in the 16 Tech Innovation District near Purdue University in Indianapolis, with sponsorship from Purdue's Provost's Office and the Office of Research. This initiative offers an opportunity to enhance research collaborations with other universities and medical industries and focus on innovation surrounding health equity within the urban community.

Disclosures

- **Presenter Disclosure**: Financial: Joshua Alexander is an employee of Purdue University and has past research support from: The National Institutes of Health; The Indiana Clinical and Translational Sciences Institute; The William Demant Holding Group; Sonova Holding AG. He is a paid consultant for Creare, LLC on an NIH SBIR project to develop an open-source, master hearing aid. Dr. Alexander is the recipient of speaker honoraria from Signia, Oticon, Phonak, Starkey, and ReSound hearing aid companies. He received an honorarium for presenting this course. Non-financial: Joshua Alexander has no relevant non-financial relationships to disclose.
- **Content Disclosure**: This learning event does not focus exclusively on any specific product or service.
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Learning Outcomes

After this course, participants will be able to:

- Identify the key advancements in AI technology that have been integrated into modern hearing aids.
- Explain how AI algorithms in hearing aids adapt to users' listening environments and preferences.
- Describe the role of sensors and AI in enhancing hearing aid functionality.

The Need for AI Hearing Aids

- Making sound loud is easy
  - ***"One of the most important jobs of a hearing aid is to <u>control</u> the amplification process by attenuating the right sounds at the right frequencies, times, and direction of arrival"***
- **Challenges**
  - Assumptions about what is meaningful to the user and what the *average* person's ear and brain need to process the information
  - What is meaningful to the user is not always speech and does not always arrive from the front

(Alexander 2021; doi: 10.1055/s-0041-1735174)

What is AI?

- Artificial Intelligence (AI) refers to the creation of systems that can perform tasks typically requiring human intelligence, such as **learning, decision-making, and pattern recognition**

- AI systems **improve their performance** by
  1. Analyzing vast amounts of data
  2. Identifying patterns
  3. Making predictions based on this data

Subtypes of AI

1. **Machine Learning (ML):** a subset of AI where systems learn from data and improve over time without being explicitly programmed
    - Uses algorithms to find patterns in data
    - Once the system "learns" from this data, it can make decisions or predictions

2. **Deep Learning:** a more advanced subtype of machine learning that uses neural networks with multiple layers (hence "deep") to process complex data
    - Neural networks mimic the human brain by processing data through interconnected layers, with each layer refining the information further

Machine Learning Analogy

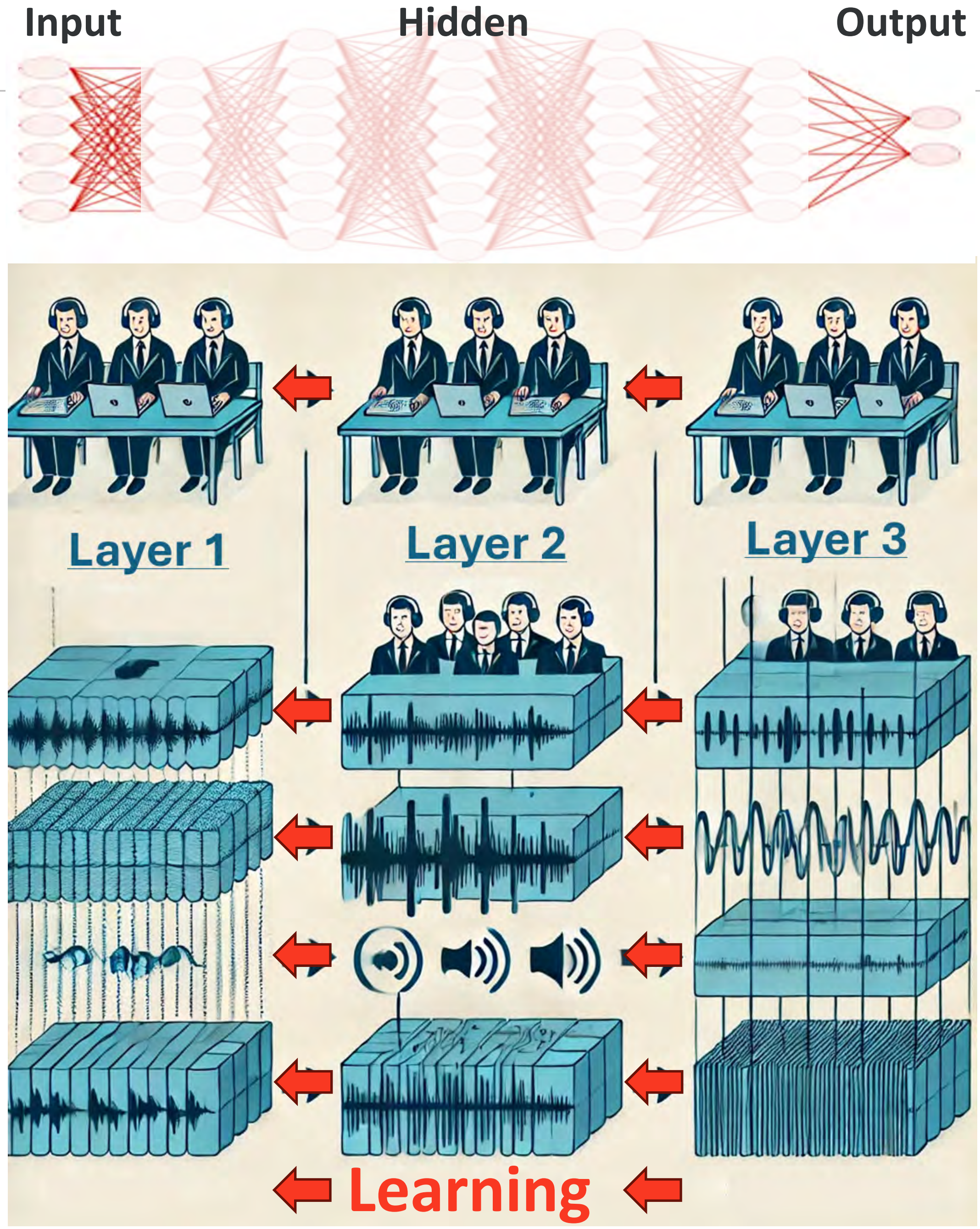
Imagine you have an audiologist who follows a user around, helping them adjust their hearing aid settings throughout the day. Over time, this audiologist becomes better at predicting the user's needs.

DNN Analogy

A neural network is like many **teams of audiologists** working together to analyze a patient's hearing complaints

Each layer (*millions to billions*) in the neural network is like a team of audiologists with similar expertise, with each audiologist like a 'neuron.'

The job gets passed from one team to the next. Each team refines the information and adds their expertise before passing it to the next team.



Machine vs. Deep Learning

Aspect	Machine Learning	Deep Learning
Structure and Complexity	Works with **structured data**, often requiring **human intervention** to select features	Uses neural networks with many layers to **automatically** learn from **structured and unstructured data**
Data Processing	Requires **structured data**, struggles with unstructured data unless features are **manually extracted**	Handles **unstructured data** and **automatically** learns features using multi-layered neural networks
Learning Ability	Improves with more data but **plateaus**; requires **human intervention** to tune parameters	Continues to **improve with larger datasets**; highly data-hungry, learns complex patterns **automatically**
Applications	Used for **less complex tasks** like predictive analytics, pattern recognition, and recommendation systems	Used for **more complex tasks** like image recognition, natural language processing, and real-time sound processing
Computation Power	**Computationally efficient**, can run on standard computers	Requires **substantial computational power** and specialized hardware like GPUs

- **Key Takeaway**
  - **Machine Learning** efficiently focuses on solving specific problems with structured data, requiring human input to define the features
  - **Deep Learning** uses complex neural networks to process unstructured data and solve more complex problems with minimal human intervention
  - In the context of hearing aids, **deep learning** enables more sophisticated sound processing, while **machine learning** can handle simpler tasks like adjusting settings based on the environment

Devices and Timing of AI Processes

- **Supercomputers**
  - Used in the research and development phase for designing algorithms based on past data
- **Cloud** (*also supercomputers*)
  - Processes large amounts of data and continuously updates hearing aid algorithms by learning from the usage patterns of many users
  - While most cloud-based AI improvements are made after the fact (*i.e.*, not in real-time during active use), they provide ongoing algorithm improvements that can be downloaded to hearing aids

Devices and Timing of AI Processes

- **Smartphones**
  - Act as intermediaries, processing AI commands and relaying data between the hearing aids and the cloud
  - Smartphones help manage non-real-time processes like syncing settings and updates

- **Hearing Aids**
  - AI-based solutions may be hard coded on the chip
  - Real-time AI processes (*ML and relatively shallow neural networks*) may occur within the hearing aids, where the AI must adjust in real time for tasks like noise reduction and sound adaptation

HatGPT

- HatGPT is a fun acronym: "**H**earing **A**id **T**echnology **G**uided by **P**redictive **T**echniques"
  - Combines AI, machine learning, and deep learning to predict and adapt to users' hearing needs in various environments
  - Uses data-driven predictions to optimize sound processing and enhance the listening experience
  - AI in hearing aids, exemplified by HatGPT, is transforming how audiologists can deliver customized care by leveraging advanced data analysis and predictive techniques

https://www.audiologyonline.com/articles/20q-artificial-intelligence-in-hearing-28996

Quasi-Historical Timeline of AI in Hearing Aids

Cloud-Based AI

Data-based (ML) systems

DNN-based systems & predictive models

Rule-based systems

2000's 2010's 2020's

NAL-NL1

Environmental Classification

Self-tuning

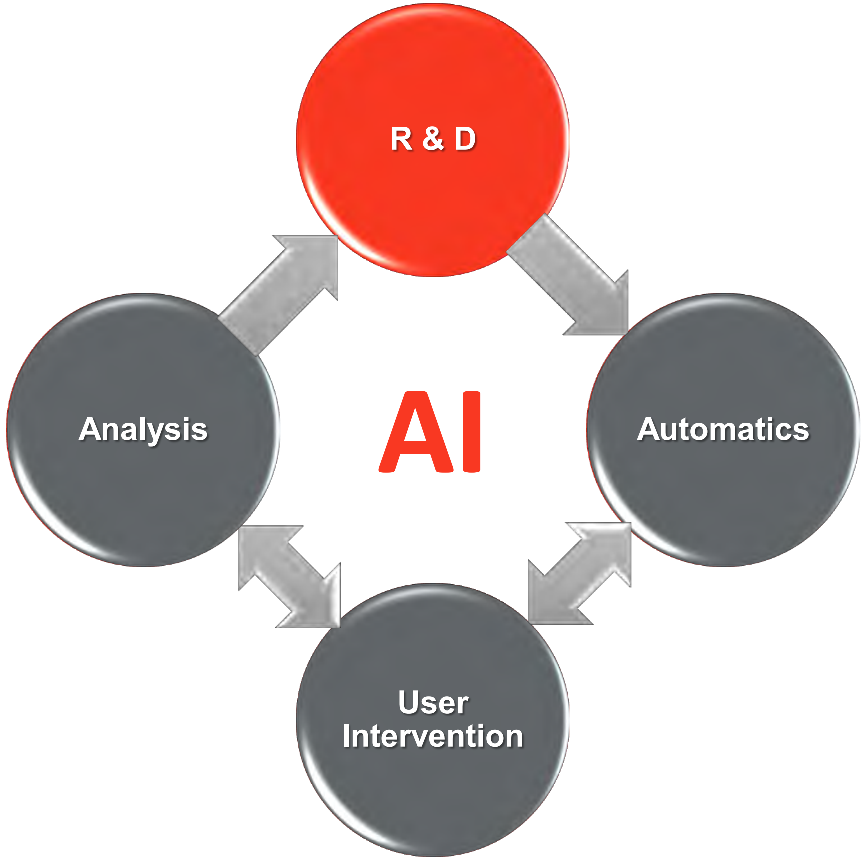
User Engagement and Health Monitoring

Speech Enhancement & Noise Reduction

R&D and Quality Control

- AI in hearing aids has evolved from simple automation to advanced, data-driven systems

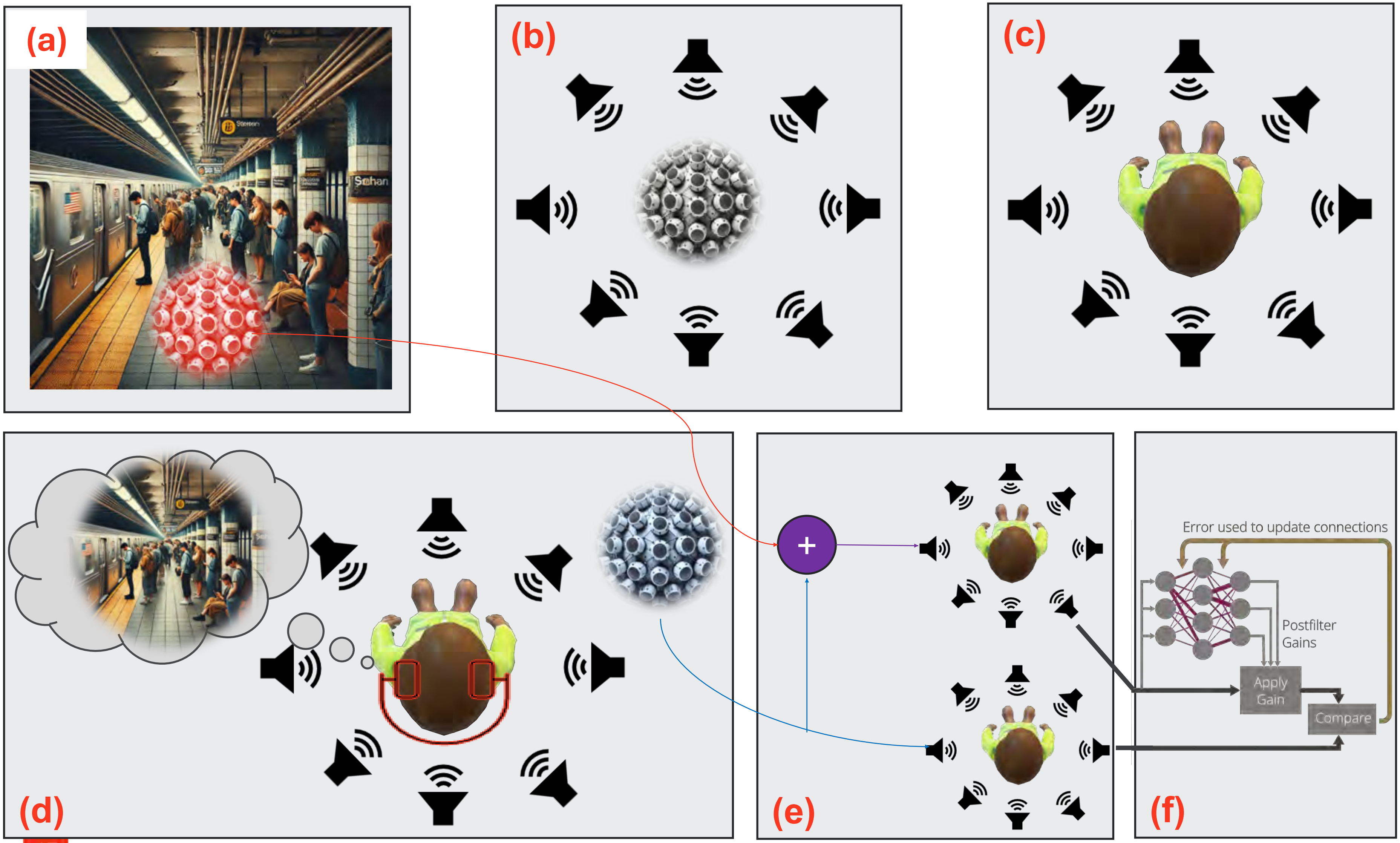
Ideal Cyclical Integration of AI in Hearing Aids



AI in Research & Development

- **Algorithm Development**
  - Researchers can train AI algorithms to understand complex listening environments (10^4 – 10^7 samples)
    - Adaptive algorithms that can automatically adjust hearing aid settings based on the acoustic environment
    - Deep learning models can be trained on vast datasets to improve real-time algorithms that separate speech from noise
  - AI-driven text-to-speech algorithms can be used to predict how humans will perceive processed speech in different conditions, enabling engineers to rapidly test and refine algorithms, thereby reducing R&D time

DNN-Based Noise Reduction



DNN-Based Noise Reduction

a) Noisy listening environments are recorded with a spherical microphone array.

b) The microphone array is placed in the center of a loudspeaker array. The transfer functions from all loudspeakers to all microphones are measured.

c) The transfer functions are inverted to reproduce the recorded listening environment at the center of the array.

d) Target audio is recorded by having one or more participants listen to noise recordings via open headphones while conversing in a quiet environment.

e) The acoustic scene is obtained by summing the noise and target recordings. Target and noisy sound signals are rendered to hearing aid microphones and used for neural network training.

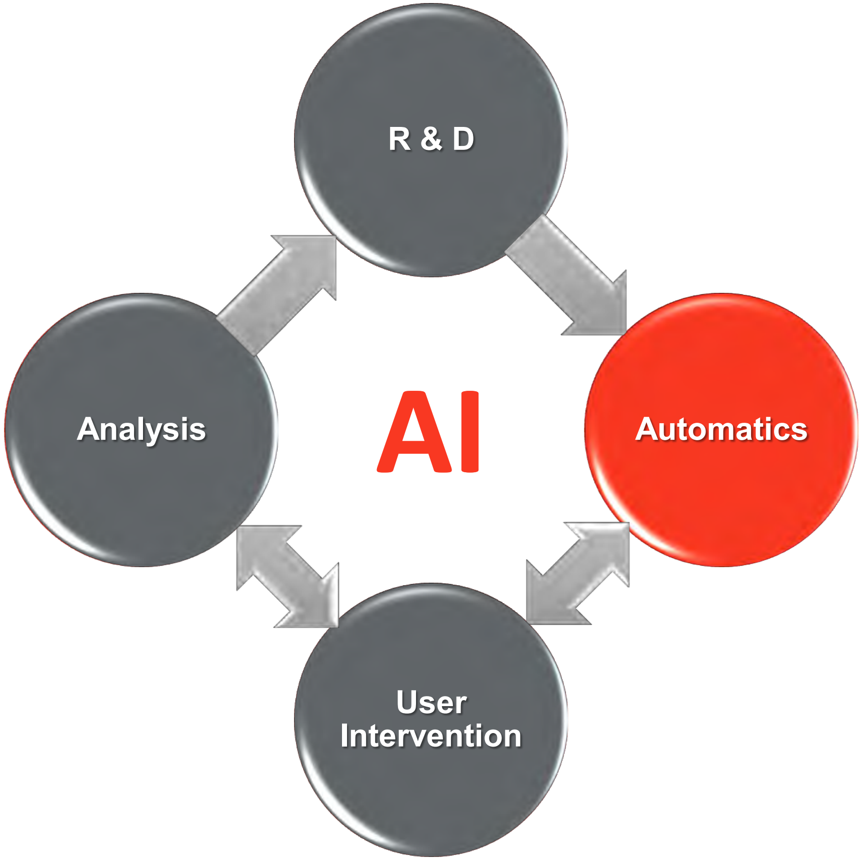
f) A neural network is trained to perform postfiltering. The neural network is used to compute postfilter gains for examples of noisy audio from the training database. These postfilter gains are applied to the noisy signals, and the result is compared to the underlying clean target signal using a loss function. The neural network connections are updated so that the postfiltered noisy signal is more similar to the underlying clean target.

(Andersen *et al.* 2021; doi: 10.1055/s-0041-1735134)

DNN-Based Noise Reduction

- Can use directionality and binaural beamforming systems to inform the algorithm to get better estimates of SNR across time and frequency while presenting the user with a **broader microphone response**
  - May achieve improvement in SNR and speech intelligibility equivalent to using directionality
  - Directionality, especially beamforming, requires the user to keep the person or thing they want to listen to in the beam of focus, which can be difficult in multi-talker environments where the target talker may change unexpectedly

Ideal Cyclical Integration of AI in Hearing Aids

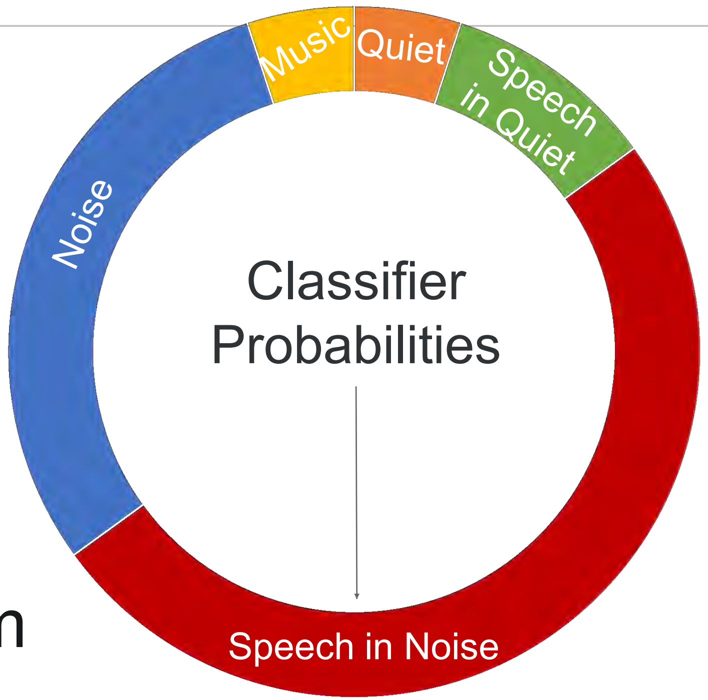


Key Problems Addressed by Environmental Classifiers

- Hearing aid users frequently move between different acoustic settings (e.g., quiet rooms, noisy streets, restaurants, and outdoor areas)

- Without classifiers, manual adjustments would be required to optimize sound processing in each environment, making hearing aids less user-friendly and more cumbersome to use
  - Constant manual adjustments can cause fatigue and inconvenience, reducing the overall effectiveness of hearing aids

What Classifiers Do



- They sample the listening environment and generate probabilities for each of the options in the automatic program
- The hearing aid switches to the option with the highest probability; updates as the listening environment changes

- **Classifiers are often trained using AI**
  - How the hearing aid **responds** (*i.e.*, program and features that provide an optimal acoustic solution) after classifying the environment is often trained by AI

Evolution of Environmental Classification in Hearing Aids

- **Early Classifiers (2000s)**
  - Early classifiers required engineers to create rule-based predictions for different environments, based on overall sound levels and types (e.g., signal-to-noise ratio)
  - Limitations stemmed from incomplete understanding of the complex acoustic environment

- **Machine Learning Integration**
  - Classifiers today are trained on vast datasets of real-world acoustic signals, allowing hearing aids to **adapt more accurately to dynamic environments**
    - Accuracy across a wide-variety of environments, including environments that are not commonly encountered is crucial

Acoustic Classifiers Can and Do Fail

- **Fail to accurately capture**
  - The listening environment
  - The user's listening needs
  - The user's listening intents

Listening Needs

Effective Directionality

"Mental Spatial Map"

Directional Focus

Environmental Awareness

- Monaural beamforming
- Binaural beamforming

Mediated by:

- Acoustic coupling to the ear
- Independent/joint signal processing

- Pinna acoustics → **Monaural cues**
- Interaural time differences (ITDs)
- Interaural level differences (ILDs)

Low Freq.

Binaural cues

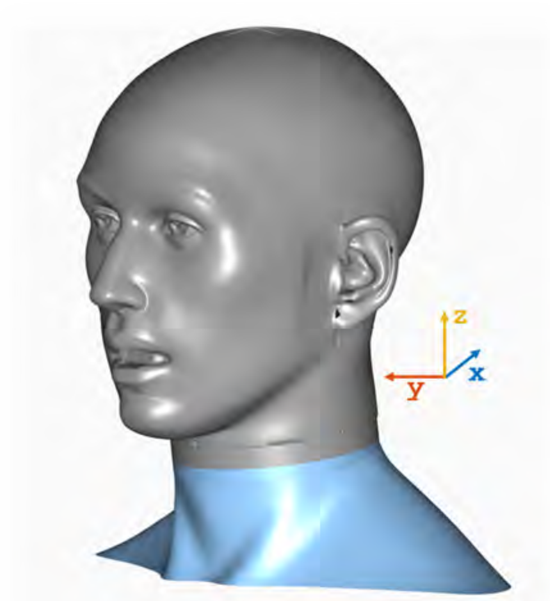
High Freq.

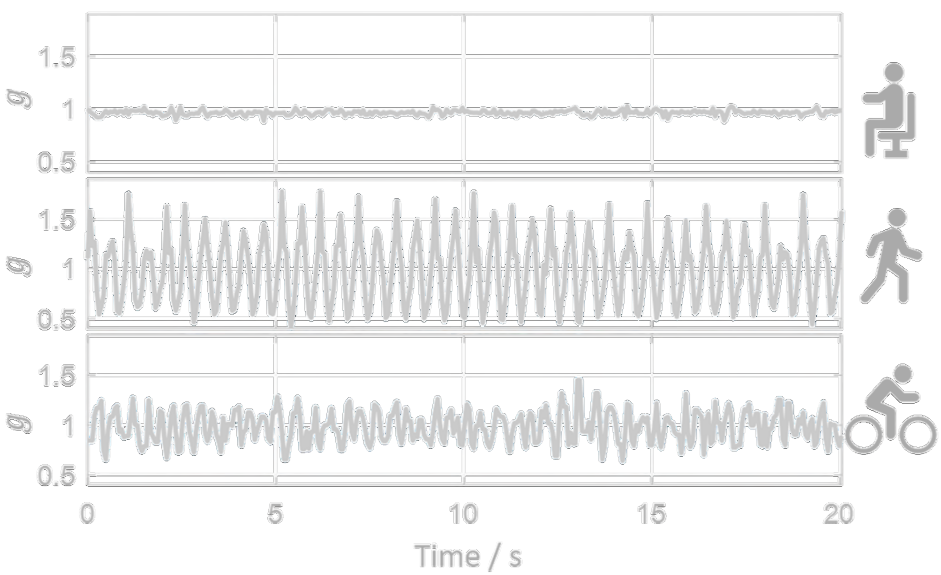
Listening Intents

Two individuals can be exposed to the **same acoustics** in the same listening environment but require different signal processing solutions if they have **different listening intents**

Sensors

- Dual microphones and binaural processing
- Motion sensors
  - Accelerometers: measure linear acceleration and detect changes in speed or direction
  - Gyroscopes: measure rotational motion or angular velocity around an axis
  - Magnetometers: detect magnetic fields by finding the direction of the Earth's magnetic field (like a compass)
- AI can be used to develop algorithms that incorporate sensor data
  - Develop algorithms that learn how to **combine data** from multiple sensors (microphones, motion, etc.) to better understand the user's environment
  - Learn from **large datasets** to understand patterns of behavior and environmental conditions, using those patterns to optimize the hearing aid's response in various situations
- Hearing aids can use sensor input and AI to adapt to dynamics





(Branda & Wurzbacher, 2021; doi: 10.1055/s-0041-1735132)

Inferring Listening Intent through Head Movement

- **Action:** When a user turns their head toward a sound source, such as a dinner companion in a noisy restaurant, it typically indicates a desire to focus on that conversation over other sounds in the environment
  - **Hearing aid:** Adjusts the microphones to narrow focus on the direction of focus

(Higgins *et al.* 2023; doi: 10.3389/fpsyg.2023.1183303

Inferring Listening Intent through Head Movement

- **Action:** In a setting with multiple conversations, frequent head turns towards different speakers, such as during a family gathering, suggest the user is trying to switch focus between conversations
  - **Hearing aid:** Adjusts to omni-directional or wide-directional mode to allow the user to scan their environment and then narrows if the head-turning stops

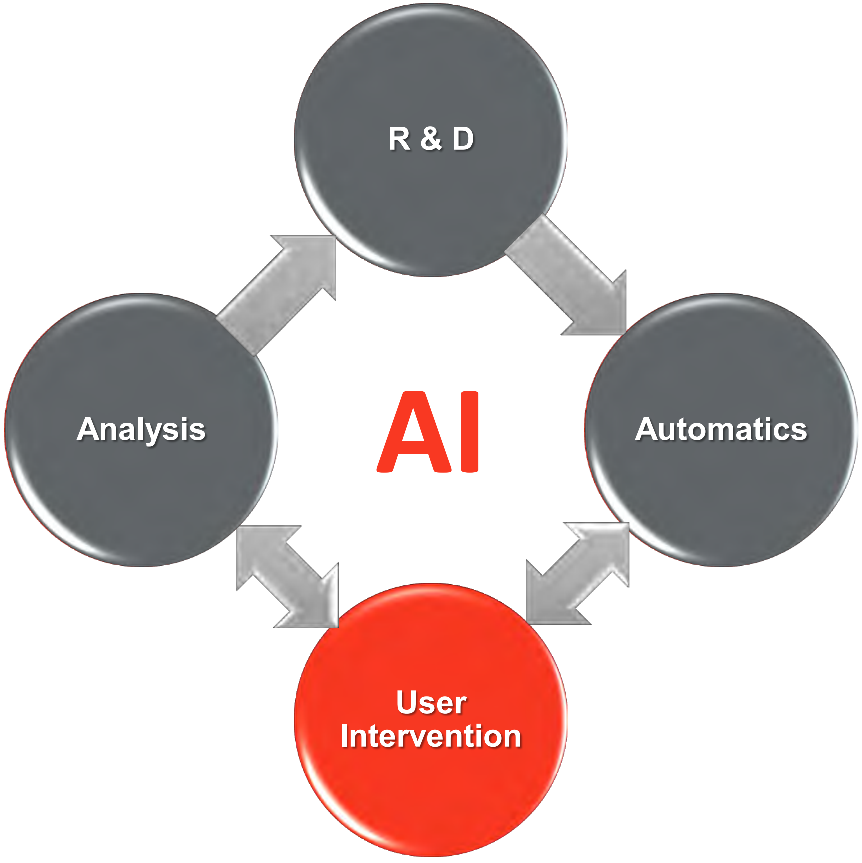
(Higgins *et al.* 2023; doi: 10.3389/fpsyg.2023.1183303

Inferring Listening Intent through Head Movement

- **Action:** A subtle head tilt or leaning in towards a speaker, such as during a large social gathering, indicates difficulty hearing or increased attention to a particular conversation, especially in noisy environments
  - **Hearing aid:** Adjusts to narrow beam forming and aggressive noise reduction

(Higgins *et al.* 2023; doi: 10.3389/fpsyg.2023.1183303

Ideal Cyclical Integration of AI in Hearing Aids



Q2, Q4

Learning from User Interactions

- **Behind the scene learning from user adjustments**
  - AI captures how users adjust their hearing aids in different environments
  - The data helps AI fine-tune automatic settings for future scenarios to create a more personalized user experience
- **Continuous improvement through AI**
  - Over time, the hearing aid becomes smarter and more attuned to the user's preferences

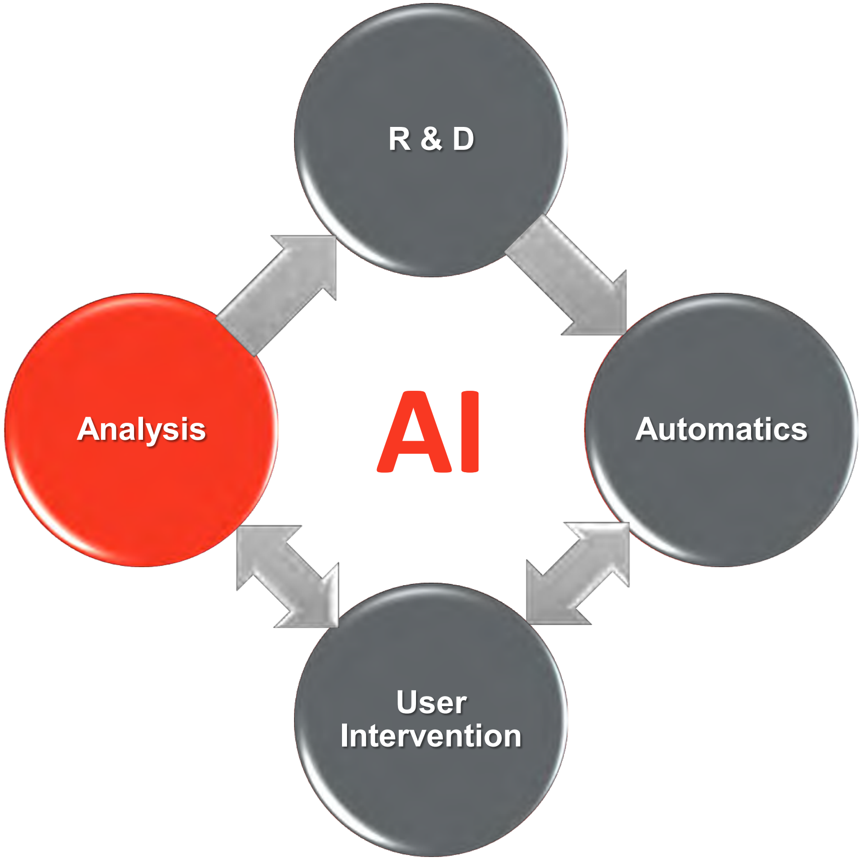
User Interaction with AI When Automatics Fail

1. User works with AI to find an optimal solution
   - The user provides input through an app or hearing aid interface
   - AI refines the settings in real time based on user feedback
   - **AI Learns**
     - AI adapts to the user's preferences and future listening situations based on the feedback provided
     - **Example:** If the user adjusts settings in a noisy restaurant, AI remembers this and improves its future automatic responses in similar environments
     - **Crowdsourced data:** AI can aggregate data from multiple users to refine the algorithms for all users based on collective preferences

User Interaction with AI When Automatics Fail

2. **User engages AI to automatically fine-tune settings**
   - The user interacts briefly with the hearing aid or app (e.g., a double-tap or pressing a button)
   - AI activates more advanced processing to adjust settings without requiring further user input, resulting in **real-time optimization**
     - Fine adjustments to parameters like volume, noise reduction, speech enhancement, and directionality on the fly
     - **Example:** In a crowded space, automatically adjust microphone focus and amplification to enhance speech clarity and reduce background noise

Ideal Cyclical Integration of AI in Hearing Aids



AI in Research & Development

- **User data analysis**
  - AI is used to analyze large datasets to improve hearing aid performance
  - AI systems in the cloud aggregate data from many users to continuously improve hearing aid algorithms
    - Make ongoing adjustments and improve future firmware updates for existing products
    - Refine or create **smarter and more responsive** algorithms for the next generation of products

AI in Quality Control

- **Prevent performance degradation**
  - AI can help identify potential issues before they become noticeable to users by monitoring streaming stability, battery performance, hardware integrity, etc.
- **Proactive maintenance**
  - Detecting patterns of battery issues across multiple users enables manufacturers to address the problem at a larger scale
- **Ensure hearing aid longevity and reliability**

AI and Health Monitoring

- **Health monitoring**
  - Monitor physical activity and social engagement
  - Fall detection systems in hearing aids outperform traditional neck-worn devices
  - Track physical activities and interactions

- **Personal hearing coach**
  - Smartphone apps act like personal trainers
    - Track hearing aid use
    - Promote consistent engagement
    - Provide data for audiologists to optimize settings

Making Hearing Aids Smarter with Smartphones

- **Voice command control**
  - AI-driven virtual assistants allow users to control their hearing aids using voice commands, making adjustments easy and intuitive

- **Cloud connectivity for advanced features**
  - Hearing aids can connect to the cloud through smartphones to access real-time features, such as language translation

Some ways AI Helps Improve Hearing Aid Functionality

- System design (e.g., development of classification systems)
- Data analysis
- Environmental noise reduction
- Healthable technology
- R&D and Quality Control

Summary of AI Features

AI Feature	What is it
Adaptive Sound Processing	Automatic adjustments to different environments (e.g., noise reduction, directional microphones)
Personalization and Learning Capabilities	AI that learns from user preferences and adapts settings over time
Smartphone Integration	Ability to control hearing aids via smartphone (e.g., voice commands, app controls)
Health Monitoring Features	Sensors for health tracking, such as step counting and fall detection
Real-Time AI Adjustments	On-demand AI adjustments for sound optimization in real-time
Cloud-Based Updates and Learning	Support for cloud-based updates to improve performance over time

Your Role with AI

- You now have access to tools that help fine-tune and optimize hearing aids based on ongoing user feedback and real-time environmental data
- **AI can support, not replace, your expertise**
  - AI systems can automate some processes, but your role as an audiologist is still crucial
  - **Patient care:** You are essential in guiding AI use, interpreting results, and ensuring the best outcomes for patients based on their unique needs
- **AI as a collaborative partner**
  - Use AI to complement your clinical knowledge
  - AI can manage ongoing adjustments and collect data, but the human touch is key to understanding patients' emotional, social, & psychological needs

Thank you

Joshua M. Alexander, PhD, CCC-A

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