Evaluating Auditory Contexts and Their Impacts on Hearing Aid Outcomes with Mobile Phones

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Hearing Loss in US

- 35 million people in the US have hearing loss
  - untreated → communication difficulties, depression, dementia etc.
- Primary intervention is hearing aid
  - ≃ 50% users satisfied with their performance in noise
Hearing Loss in US

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Underlying causes of user dissatisfaction are poorly understood
Auditory Context
Auditory Context

social interaction
Auditory Context

social interaction

activity
Auditory Context

social interaction

activity

acoustic environment
Existing methods
Existing methods

- Speech-in-noise tests: assess aspects of hearing aid technology
- not representative of real-world auditory contexts
Existing methods

• Speech-in-noise tests: assess aspects of hearing aid technology
  • not representative of real-world auditory contexts
• Manual data collection: self-reports or diary methods
  • subjective, memory bias, scalability
Existing methods

- Speech-in-noise tests: assess aspects of hearing aid technology
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- Manual data collection: self-reports or diary methods
  - subjective, memory bias, scalability

Existing evaluation methods are poor predictors of real-world performance
AudioSense

- Provides clinicians with subjective and objective measures of hearing aid outcomes and auditory contexts
  - subjective: Ecological Momentary Assessment (EMA)
  - objective: derived from audio and GPS
  - data is collected in real-time and in-situ
  - EMA has been previously used by Henry et al. and Galvez et al.
  - we collect sensor data, track subject compliance in real-time


AudioSense: Enabling real-time evaluation of hearing-aid technology in-situ

CBMS 2013
Remainder of the talk
Remainder of the talk

What are the typical auditory contexts?
Remainder of the talk

What are the typical auditory contexts?

Are the hearing aid outcomes correlated?
Remainder of the talk

What are the typical auditory contexts?

Are the hearing aid outcomes correlated?

Can the hearing aid outcomes be predicted?
Field Study

• 19 older adults
  • mild-to-moderate hearing loss
  • age range: 65 - 87

• 2 hearing aids
  • Phonak Bolero Q50 : low cost, low-end adaptive directional microphone (DM) and digital noise reduction (DNR)
  • Phonak Bolero Q90 : premium level, advanced DM and DNR

• 6 sessions
  • one unaided, one application practice
  • two allotted to each hearing aid
    • DM, DNR turned on/off
Measuring the auditory context
Measuring the auditory context

Could you see the talker’s face?

acoustic environment

social interaction

activity
Measuring the auditory context

Could you see the talker’s face?

What were you listening to?

Social interaction

Acoustic environment

Activity
Measuring the auditory context

Could you see the talker’s face?

Where were you?

activity

social interaction

acoustic environment

What were you listening to?
Measuring the auditory context

- What were you listening to?
- How noisy was it?
- Where were you?
- Could you see the talker’s face?

**Social Interaction**

**Acoustic Environment**

**Activity**
Measuring the auditory context

What were you listening to?
How noisy was it?

Could you see the talker’s face?

Where were you?

How important was it to hear well?

social interaction

activity

acoustic environment
Measuring the outcomes
Measuring the outcomes

How much speech did you understand?
Measuring the outcomes

How much speech did you understand?

Could you tell where the sounds were coming from?
Measuring the outcomes

How much effort was required to listen?

How much speech did you understand?

Could you tell where the sounds were coming from?
Measuring the outcomes

How much effort was required to listen?

How much speech did you understand?

How satisfied were you with your hearing-aid?

Could you tell where the sounds were coming from?
Remainder of the talk

What are the typical auditory contexts?

Are the hearing aid outcomes correlated?

Can the hearing aid outcomes be predicted?
Remainder of the talk

What are the typical auditory contexts?

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Activity context distribution

- Conversation (up to 3)
- Conversation (more than 3)
- Listening to live events
- Listening to media
- Talking on the phone
- Non speech activity
- Passive listening activity

Activity (% surveys)

Patients

All 1 2 3 4 5 6 7
Activity context distribution

- Conversation (up to 3)
- Conversation (more than 3)
- Listening to live events
- Listening to media
- Talking on the phone
- Non speech activity
- Passive listening activity

Activity context distribution (31%)
Activity context distribution

- Conversation (up to 3)
- Conversation (more than 3)
- Listening to live events
- Listening to media
- Talking on the phone
- Non speech activity
- Passive listening activity

33%

31%
Activity context distribution

19% Conversation (up to 3)
33% Listening to live events
31% Listening to media

AuditoryContexts - May 23, 2014
Activity context distribution

- 19% Conversation (up to 3)
- 33% Conversation (more than 3)
- 31% Listening to live events
- 10% Listening to media
- 2% Talking on the phone
- 3% Non speech activity
- 38% Passive listening activity

Significant variability across users
Noise level distribution

![Noise level distribution chart](chart.png)

Legend:
- Quiet
- Bit noisy
- Noisy
- Very noisy

Noise level (% surveys)

Patients

AuditoryContexts - May 23, 2014
Noise level distribution

- 50% Quiet

Legend:
- Quiet
- Bit noisy
- Noisy
- Very noisy

AuditoryContexts - May 23, 2014
Noise level distribution

40% Bit noisy

50% Quiet
Noise level distribution

Most of the time is spent in low noise environments

- 50% Quiet
- 40% Bit noisy

AuditoryContexts - May 23, 2014
Location context distribution

- Outdoor (Traffic)
- Outdoor (No traffic)
- Home (-10)
- Not home (-10)
- Crowd (10+)

Location (% surveys)

<table>
<thead>
<tr>
<th>Patients</th>
<th>Location Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
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<tr>
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<td>2</td>
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<td>6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
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</tbody>
</table>
Location context distribution

Most of the time is spent at home
Importance of activity context

- Conversation (up to 3 people)
- Conversation (more than 3 people)
- Listening to live events
- Listening to media
- Talking on the phone
- Non speech listening
- Passive listening
Importance of activity context

High importance to listening well in socially engaging activities

Relatively lower importance to passive listening activities
Importance of location context

![Box plot showing the importance of different location contexts]

- Outdoor (Traffic)
- Outdoor (No traffic)
- Home (-10)
- Not home (-10)
- Crowd (10+)

Importance on the y-axis, with outliers marked by red crosses.
Importance of location context

High importance to hearing well in unfamiliar locations
On evaluating auditory contexts

Auditory contexts:
- conversations and listening to media are most prevalent
- social engagement necessitates hearing well

Are the hearing aid outcomes correlated?

Can the hearing aid outcomes be predicted?
Remainder of the talk

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Hearing aid outcome measurement

- Several dimensions are measured:
  - speech perception (SP), listening effort (LE), loudness (LD2), activity participation (AP), satisfaction (ST), and sound localization (LCL)

- Multiple dimensions help in understanding the underlying factors affecting the assessment

- Combining correlated outcomes can
  - reduce inherent noise
  - ease prediction
## Existence of correlation

<table>
<thead>
<tr>
<th></th>
<th>SP</th>
<th>LE</th>
<th>ST</th>
<th>LCL</th>
<th>LD2</th>
<th>AP</th>
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- Spearman’s rank correlation
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- Spearman’s rank correlation
- Moderate correlation (0.34 - 0.65)
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- Spearman’s rank correlation
- Moderate correlation (0.34 - 0.65)
- Consider the four most correlated outcomes to compute the combined score
Creating combined score
Creating combined score

\[ f_1 : \text{LCL} \mapsto \text{LE} \]
Creating combined score

$f_1: \text{LCL} \mapsto \text{LE}$

$f_2: \text{SP} \mapsto \text{LE}$
Creating combined score

$f_1 : \text{LCL} \leftrightarrow \text{LE}$

$f_2 : \text{SP} \leftrightarrow \text{LE}$

$f_3 : \text{ST} \leftrightarrow \text{LE}$
Creating combined score

- Mapping to LE as it has the widest distribution
- better discrimination
- $f_1, f_2, \text{and } f_3$ fit a polynomial
- Combined score (CB) = \text{avg}(LE, f_1, f_2, f_3)
Creating combined score

- Mapping to LE as it has the widest distribution
- better discrimination
- $f_1, f_2, \text{ and } f_3$ fit a polynomial
- Combined score ($CB$) = $\text{avg}(\text{LE}, f_1, f_2, f_3)$
On correlation between outcomes

Auditory contexts:
• conversations and listening to media are most prevalent
• social engagement necessitates hearing well

Correlation between outcomes:
• hearing aid outcomes are moderately correlated
• calculated a combined score

Can the hearing aid outcomes be predicted?
Remainder of the talk

Auditory contexts:
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Can the hearing aid outcomes be predicted?
Predicting the combined score
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• Challenges
  • incorporate data from all subjects while accounting for individual differences
  • should be able to capture interplay between contexts and outcomes
Predicting the combined score

• Challenges

• incorporate data from all subjects while accounting for individual differences

• should be able to capture interplay between contexts and outcomes

• We created a linear model

\[ Y = \beta + subject \cdot \sum_{x \in D} x + session \cdot \sum_{x \in D} x \]
Predicting the combined score

- Challenges
  - incorporate data from all subjects while accounting for individual differences
  - should be able to capture interplay between contexts and outcomes
- We created a linear model
  
  $$Y = \beta + \text{subject} \cdot \sum_{x \in D} x + \text{session} \cdot \sum_{x \in D} x$$
Predicting the combined score

- Challenges
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Predicting the combined score

- **Challenges**
  - incorporate data from all subjects while accounting for individual differences
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- **We created a linear model**

\[ Y = \beta + \text{subject} \cdot \sum_{x \in D} x + \text{session} \cdot \sum_{x \in D} x \]

combined score \hspace{5mm} intercept \hspace{5mm} variations by subject
Predicting the combined score

- Challenges
  - incorporate data from all subjects while accounting for individual differences
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Predicting the combined score

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- combined score
- intercept
- variations by subject
- variations by HA
- context variables
Predicting the combined score

- **Challenges**
  - incorporate data from all subjects while accounting for individual differences
  - should be able to capture interplay between contexts and outcomes
- **We created a linear model**
  \[ Y = \beta + \text{subject} \cdot \sum_{x \in D} x + \text{session} \cdot \sum_{x \in D} x \]
  - combined score
  - intercept
  - variations by subject
  - variations by HA
  - context variables
- **Terms that were not statistically significant were removed**
Evaluating the prediction
Evaluating the prediction

\[ R^2 = 0.83 \]
\[ R^2 \text{ (adjusted)} = 0.74 \]
Evaluating the prediction

The high $R^2$ supports the goodness of fit.
Evaluating the prediction

The high $R^2$ supports the goodness of fit.
Evaluating the prediction

The high $R^2$ supports the goodness of fit

85% of the time the absolute error was less than 10
Evaluating the prediction

The high $R^2$ supports the goodness of fit

10 fold cross validation based classification of good and bad outcomes was 78% accurate

85% of the time the absolute error was less than 10
On prediction of outcomes

Auditory contexts:
• conversations and listening to media are most prevalent
• social engagement necessitates hearing well

Correlation between outcomes:
• hearing aid outcomes are moderately correlated
• calculated a combined score

Outcome prediction:
• auditory contexts + hearing aid features help in understanding outcomes
Conclusion

• Hearing aid outcomes depend on auditory contexts
  • AudioSense characterizes auditory contexts and outcomes accurately using subjective and objective data captured in-situ

• The proposed methodology enables new insights
  • prevalence of auditory contexts
  • highlighting the dependence of outcomes on contexts

• Future work
  • extend study to 55 users (largest study to date)
  • use audio data to characterize auditory contexts
  • novel sampling techniques to reduce the evaluation burden
Acknowledgement

- Audiology collaborator: Elizabeth Stangl
- National Science Foundation (1144664)
- Roy J. Carver Foundation (14-43555)
- National Institutes of Deafness and Other Communication Disorders - National Institutes of Health (R03 DC012551)
Support slides follow
Distribution of outcomes

[Box plots showing the distribution of outcomes for different categories: SP, LE, ST, LCL, LD2, AP. The box plots illustrate the spread and central tendency of the data for each category.]
Distribution of outcomes

Scores are generally high, median range 71-86 across all dimensions.
Scores are generally high, median range 71-86 across all dimensions.

Score variability indicate presence of contexts with scope for improvement.
AudioSense application

- Iterative design
  - based on feedback from users
  - larger buttons, contrasting colors
High reliability except in cases of server failures
Reliability of data delivery

Overall reliability of > 90%
## Subject demographics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Statistics</th>
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</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Male 35%</td>
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<tr>
<td></td>
<td>Female 65%</td>
</tr>
<tr>
<td>Age (years)</td>
<td>Median: 70.5, Range: 65 – 87</td>
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<tr>
<td>Hearing loss onset (years)</td>
<td>Median: 12, Range: 1 – 54</td>
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<td>Employment</td>
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<tr>
<td></td>
<td>Retired 18</td>
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<tr>
<td>Duration of HA use (years)</td>
<td>Median: 8.5, Range: 0 – 40</td>
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