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# Speech Acoustics and Frequency Lowering

Joshua M. Alexander, Ph.D., CCC-A
Purdue University

# Joshua M. Alexander, PhD

Joshua Alexander is an associate professor at Purdue University in West Lafayette, Indiana. At the University of Wisconsin-Madison, he received a BS, MS, and PhD in Audiology (psychoacoustics) and researched speech perception as a post-doctoral scientist. He also completed clinical and post- doctoral fellowships at Boys Town National Research Hospital in Omaha, Nebraska. The central goal of Dr. Alexander's research is to improve speech understanding and decrease listening effort in hearing aid users. To assist in these efforts, he has developed a PC-based hearing aid simulator that is capable of replicating key features of commercial hearing aids. This tool combined with laboratory measures and models of processing at the sensory, neural, and cognitive levels allows him and his collaborators to explore how and why certain features of hearing aids affect perception and to explore factors that might explain individual differences in hearing aid benefit.

**Presenter Disclosure:**

- Financial: Joshua Alexander, an employee of Purdue University.
  - He 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 the holder of two patents on a method of frequency lowering and has a recent invention disclosure on another method.
- 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, and received an honorarium for presenting this course.
- Non-financial: Dr. Alexander has no relevant non-financial disclosures.

**Content Disclosure:** This learning event does not focus exclusively on any specific product or service.

**Sponsor Disclosure:** There is no external sponsor for this course.

# Learning Outcomes

After this course, participants will be able to

1. Describe different considerations affecting the recognition of frequency-lowered speech.
2. Identify how different speech sound classes are likely to be affected by increasing access to the high-frequency spectrum.
3. Describe how and why speech recognition can be negatively affected by frequency lowering.

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# Frequency Lowering is Ubiquitous

| Manufacturer | Feature Name | Frequency Lowering Method |
|---|---|---|
| **Widex** | Audibility Extender | Transposition (static) |
| | Enhanced Audibility Extender | Transposition (adaptive) |
| **Phonak** | SoundRecover [a] | Compression (static) |
| | SoundRecover2 | Compression (adaptive) |
| **Starkey** | Spectral iQ [b] | Spectral Envelope Warping |
| **Signia** | Frequency Compression [c] | Compression |
| **ReSound** | Sound Shaper [d] | Proportional Compression |
| **Oticon** | Speech Rescue [e] | Multilayered Transposition |

[a] Also offered by Unitron as "Frequency Compression" and by Hansaton as "Sound Restore"

[b] Also offered by Microtech as "Sound Compression"

[c] Also offered by Rexton as "Bandwidth Compression"

[d] Also offered by Beltone as "Sound Shifter" and by Interton as "Frequency Shifter"

[e] Similar to, but not the same as, what is offered by Bernafon as "Frequency Composition" and by Sonic as "Frequency Transfer"

**But it is also the most misunderstood!**

# Survey Questions

1. Do you regularly fit hearing aids?

2. Do you regularly use frequency lowering?

3. On a scale of 0-5, rate your self-confidence in making decisions about frequency lowering
   - 0 = not at all confidence
   - 5 = very confident

# Clinicians Lack Confidence

*We are trained to "know before you click"*

1. What is happening under the hood
   - Differences between manufacturers
   - Reliance on subjective labels is not enough
   - Need to explicitly know how sounds are re-mapped
     - Frequency-lowered sounds need to be **audible**
     - Frequency lowering needs to be *minimally invasive*

2. What is your goal?
   - Expected or potential outcomes

# What is happening under the hood

## Frequency Lowering Amplification Master Class

Course: #36359 | Level: Advanced | 5 Hours | ★★★★★ 171 Reviews

This 5-hour Master Class demystifies frequency lowering amplification technology, to bring a new level of understanding for clinicians and to empower clinical decision making. A review of the goals of this technology and factors that may influence its effectiveness is included, as well as general guidelines for verification using probe microphone measurements. Finally, a demonstration of the differences between the various techniques in use today concludes this comprehensive 'look under the hood' at frequency lowering amplification.

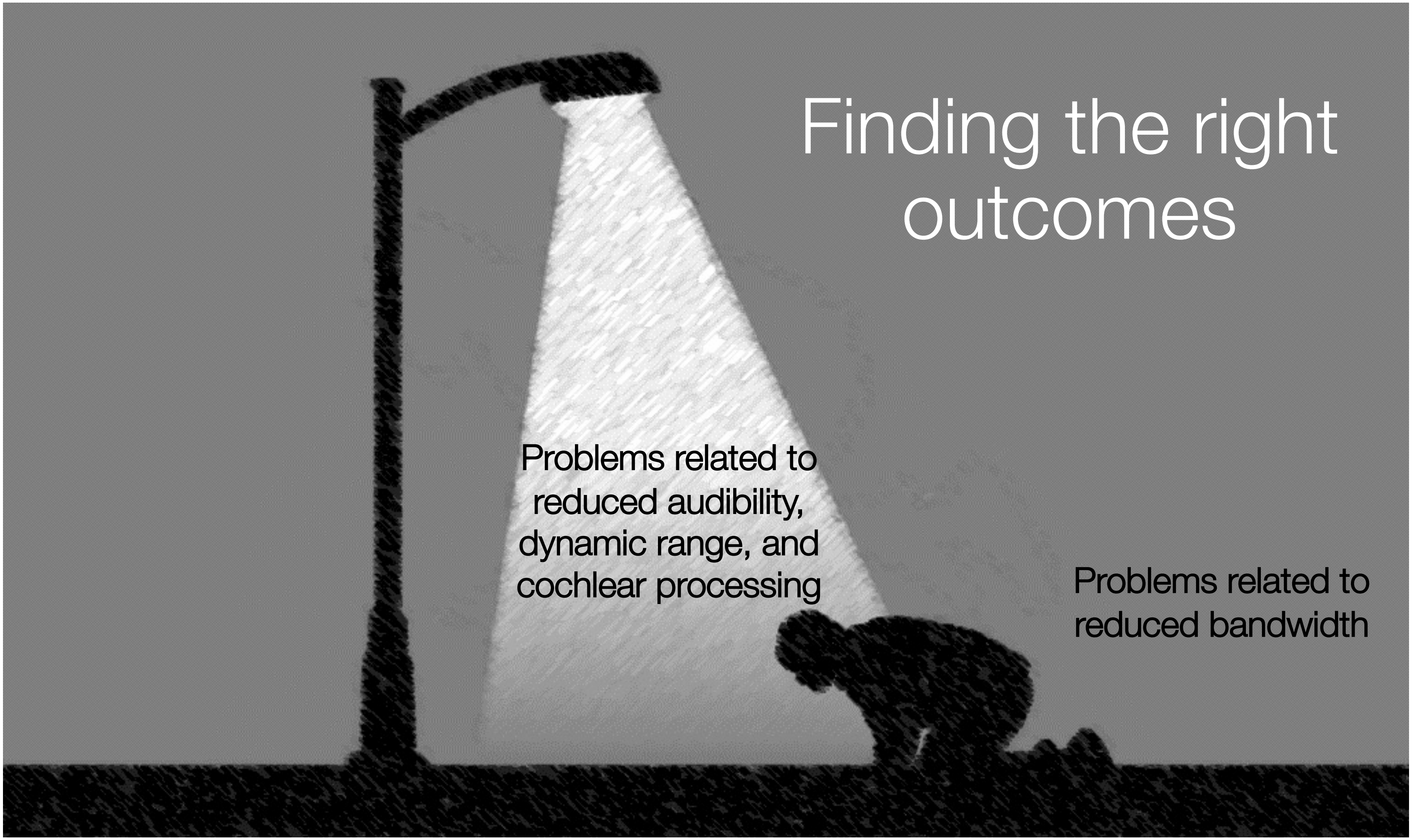
Course created on April 1, 2021

# Potential outcomes set the stage for how we approach the fitting process

1. The choices we make when selecting and programming the hearing aid
2. The method we use to verify the fit
3. How we counsel the patient about proper expectations

Q1

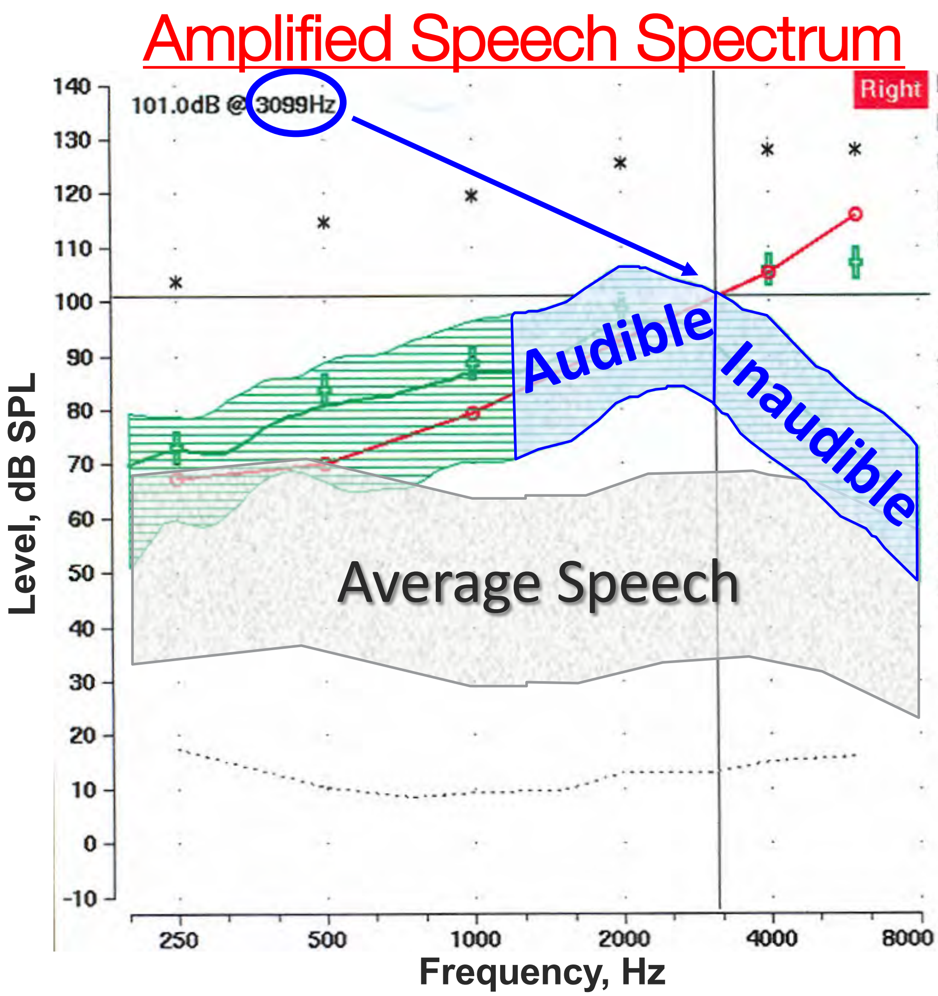
# Finding the right outcomes



Problems related to reduced audibility, dynamic range, and cochlear processing

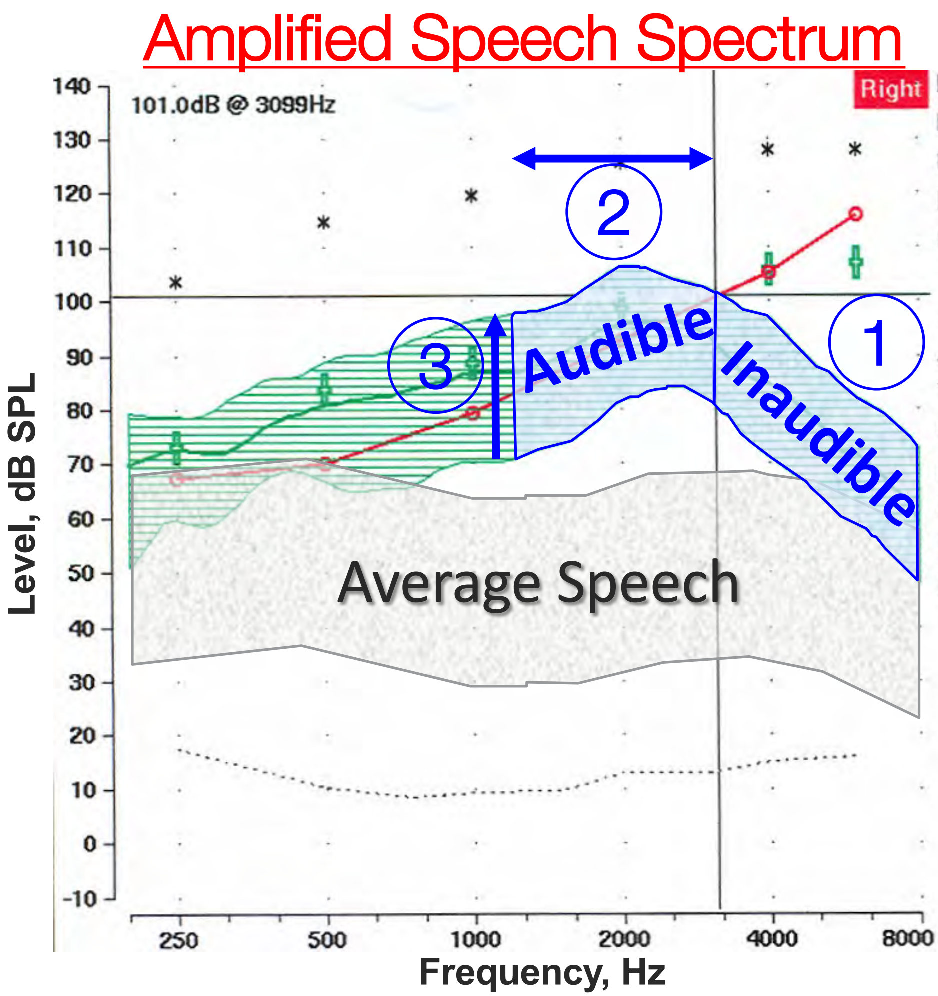
Problems related to reduced bandwidth

# Maximum Audible Output Frequency (The MAOF)




**Born:** March 30, 2009

# Net benefit from frequency lowering is limited by the following:



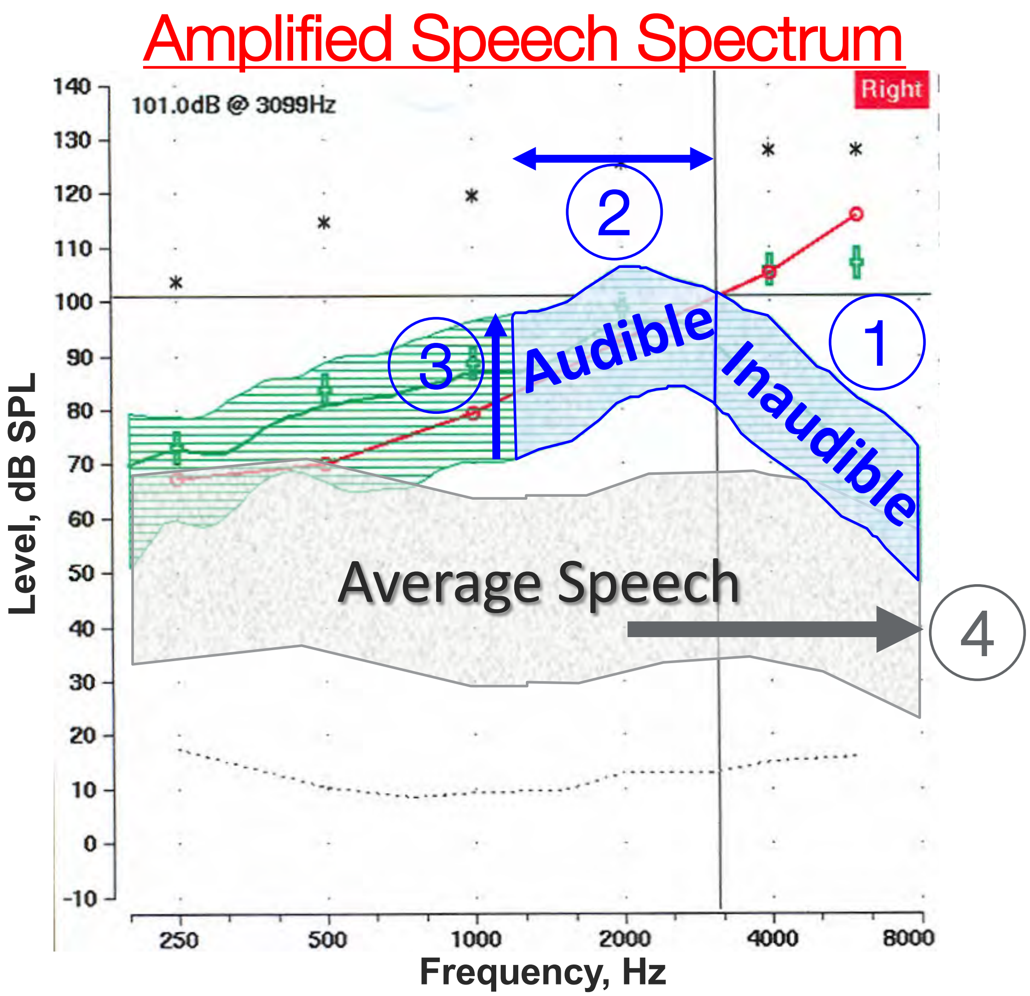
# Net benefit from frequency lowering

- Limited by the following facts:

1. Information in the high-frequencies may be truncated or distorted in the process of lowering
2. Information in the low frequencies may be displaced or masked by newly introduced information from the high frequencies
3. Re-coded high-frequency information is put at places along the cochlea where outer and/or inner hair cell functioning is likely still abnormal, albeit to a lesser extent than the places where the information would normally be transduced

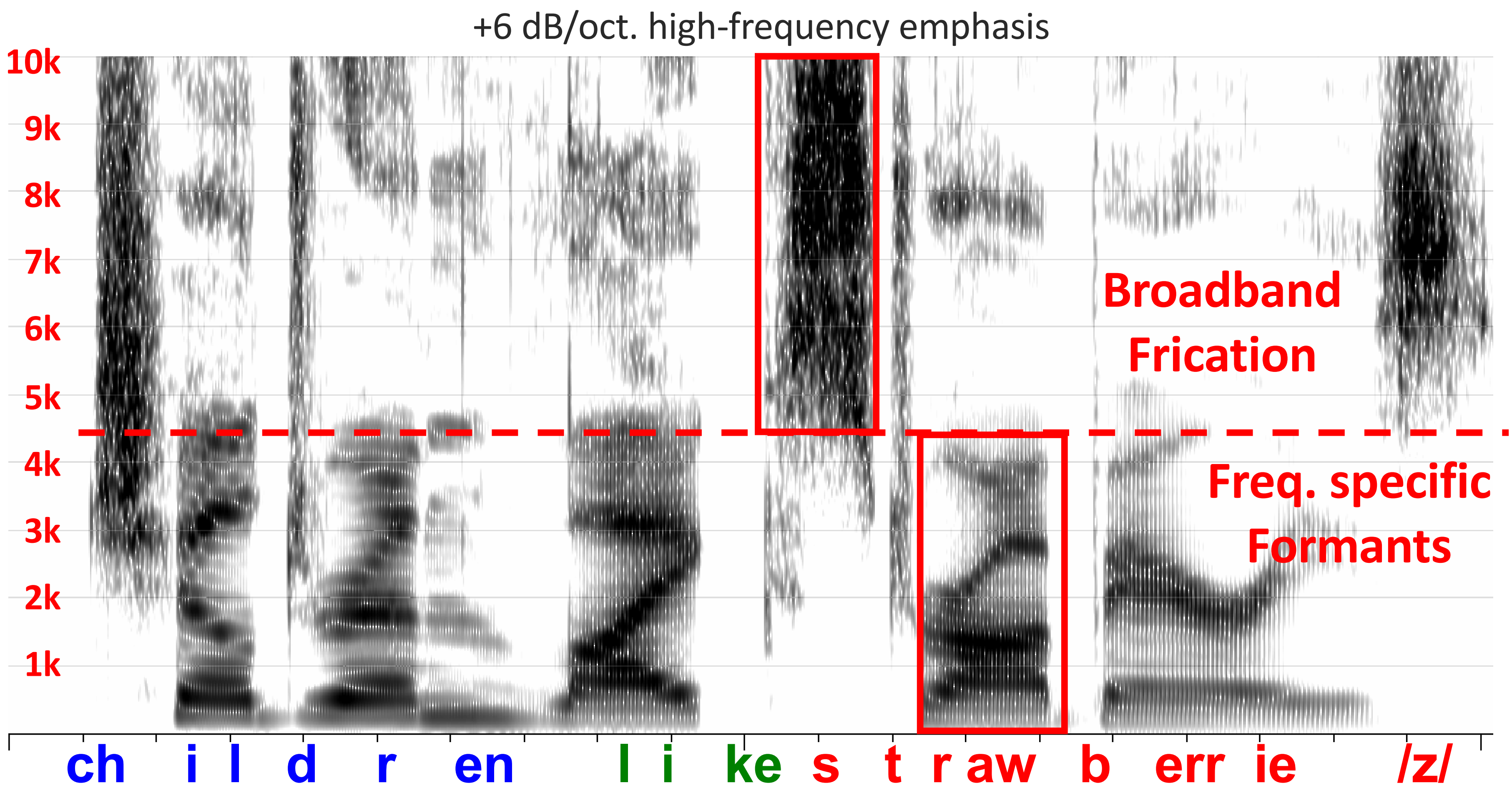
Q3

# Net benefit from frequency lowering is limited by the following:




The net loss of information due to limited bandwidth

# Speech Information



# Participants

- 10-12 *normal-hearing* adult listeners
- Why?
  1. Basic desire to understand what **increased bandwidth** does to speech information
     - If increasing bandwidth over a certain range does not improve perception of some sounds, then neither should frequency lowering
  2. Basic desire to understand what **frequency lowering** does to speech information, independent of hearing loss
     - If certain information is not available to normal-hearing listeners in the re-coded signal, we shouldn't expect it to be for hearing-impaired listeners either

# Stimuli

## Consonants (n = 12)

120 nonsense syllables (vCv) presented in **speech-shaped noise at 10 dB SNR**

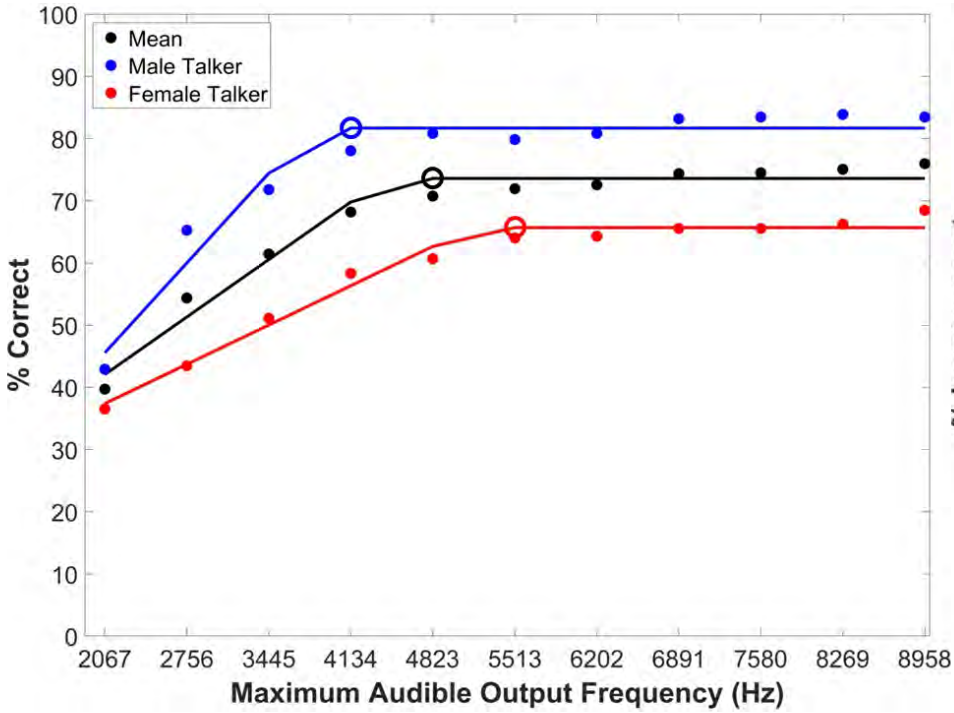
- 20 consonants
- 3 vowel contexts (/a/, /i/, /u/)
- 2 talkers (adult male and female)

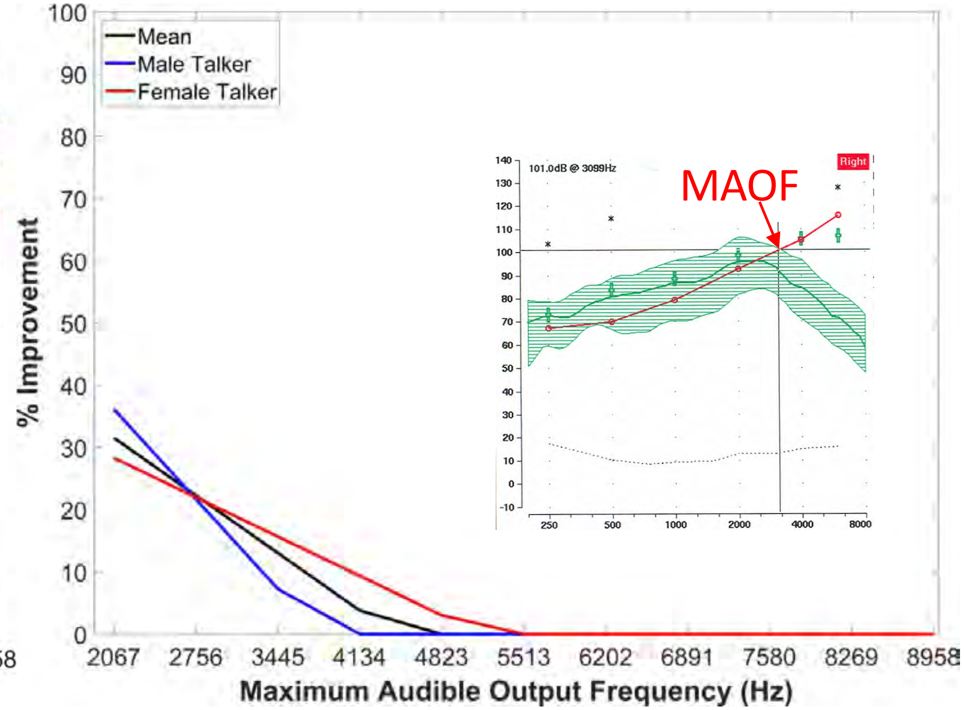
## Vowels (n = 10)

72 nonsense syllables (h-V-d) presented in **speech-shaped noise at 6 dB SNR** (Hillenbrand *et al*., 1995)

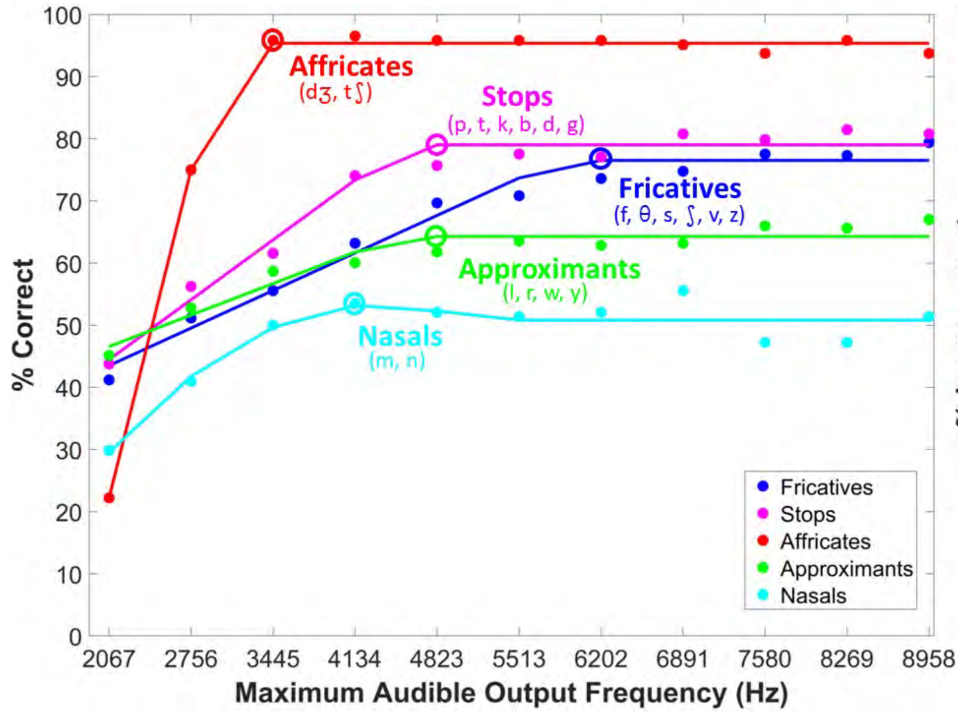
- 12 vowels
- 6 talkers (2 adult males, 2 adult females, 1 boy, 1 girl)

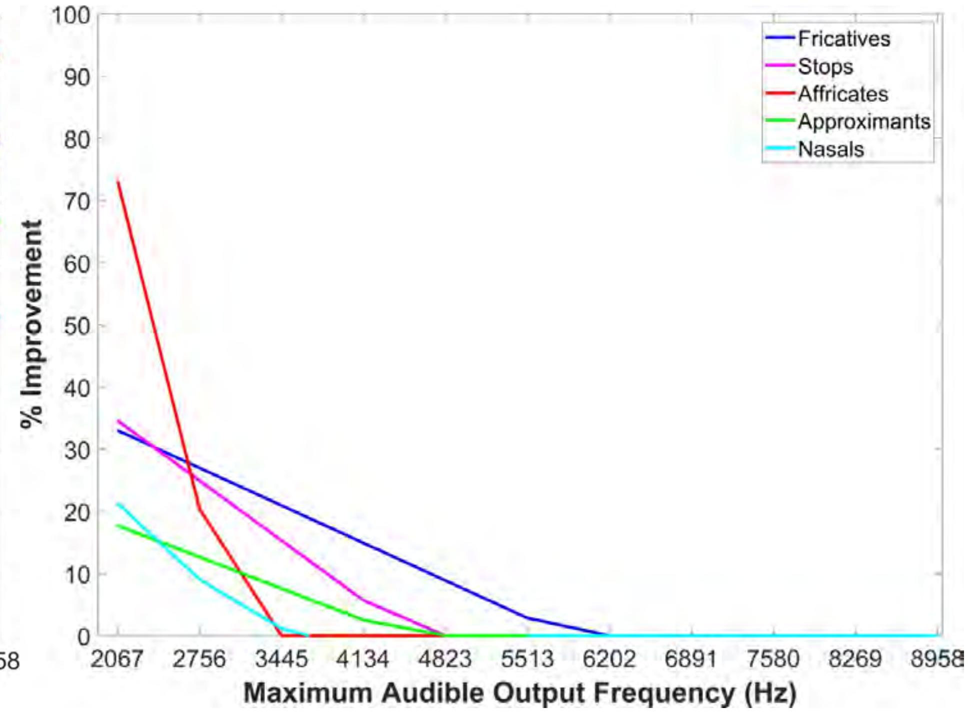
# Consonant Recognition by Talker Gender



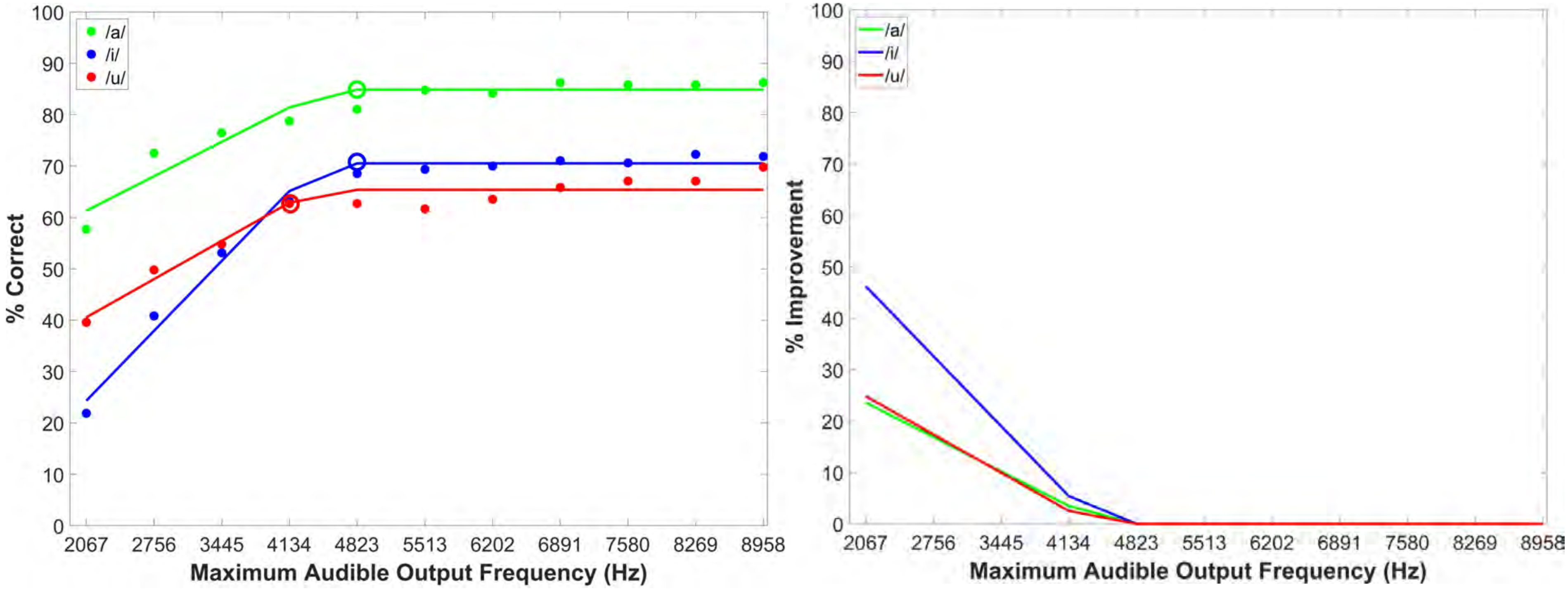



# Consonant Recognition by Manner of Articulation

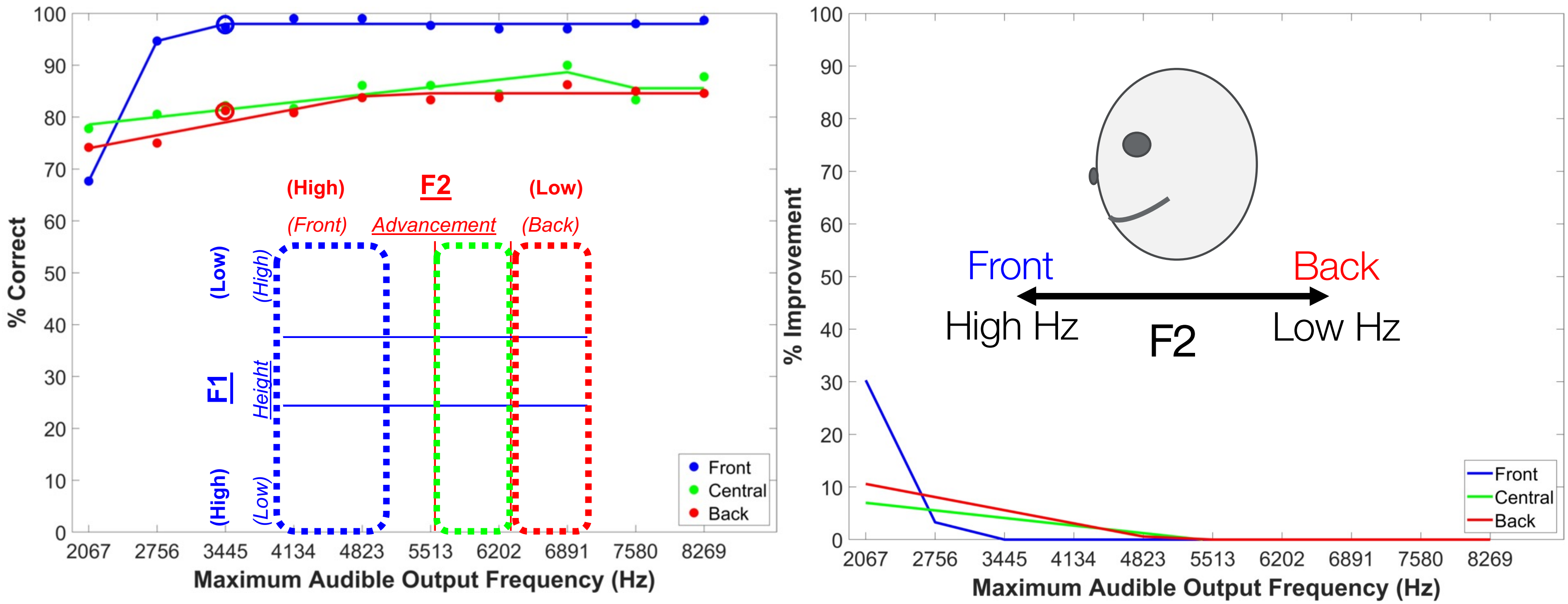


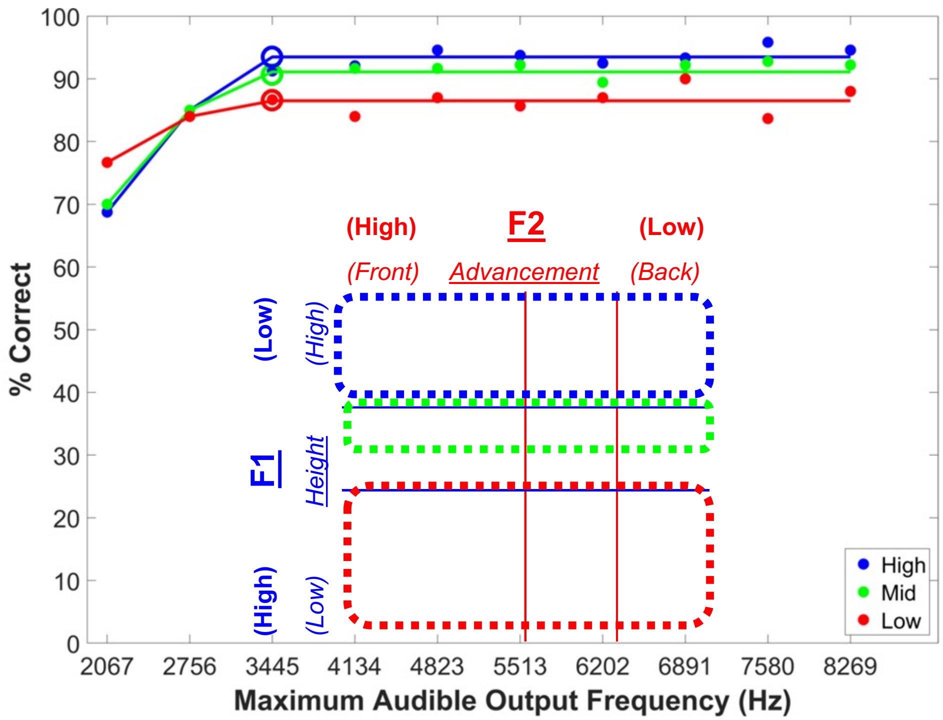
# Consonant Recognition by Co-articulating Vowels

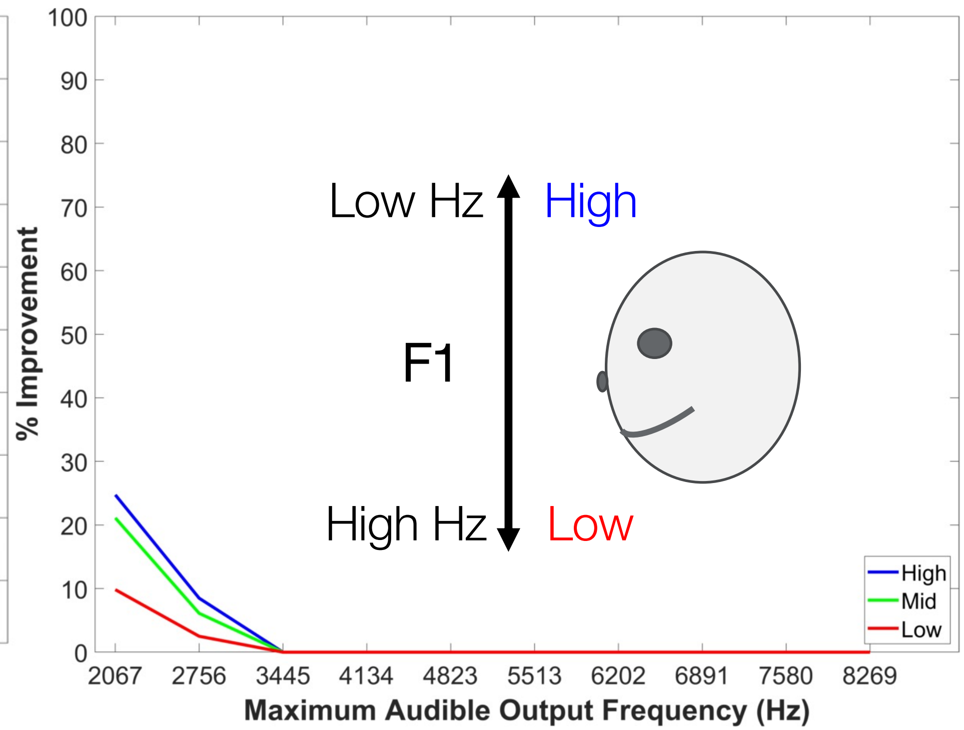


# Vowel Recognition by Tongue Advancement



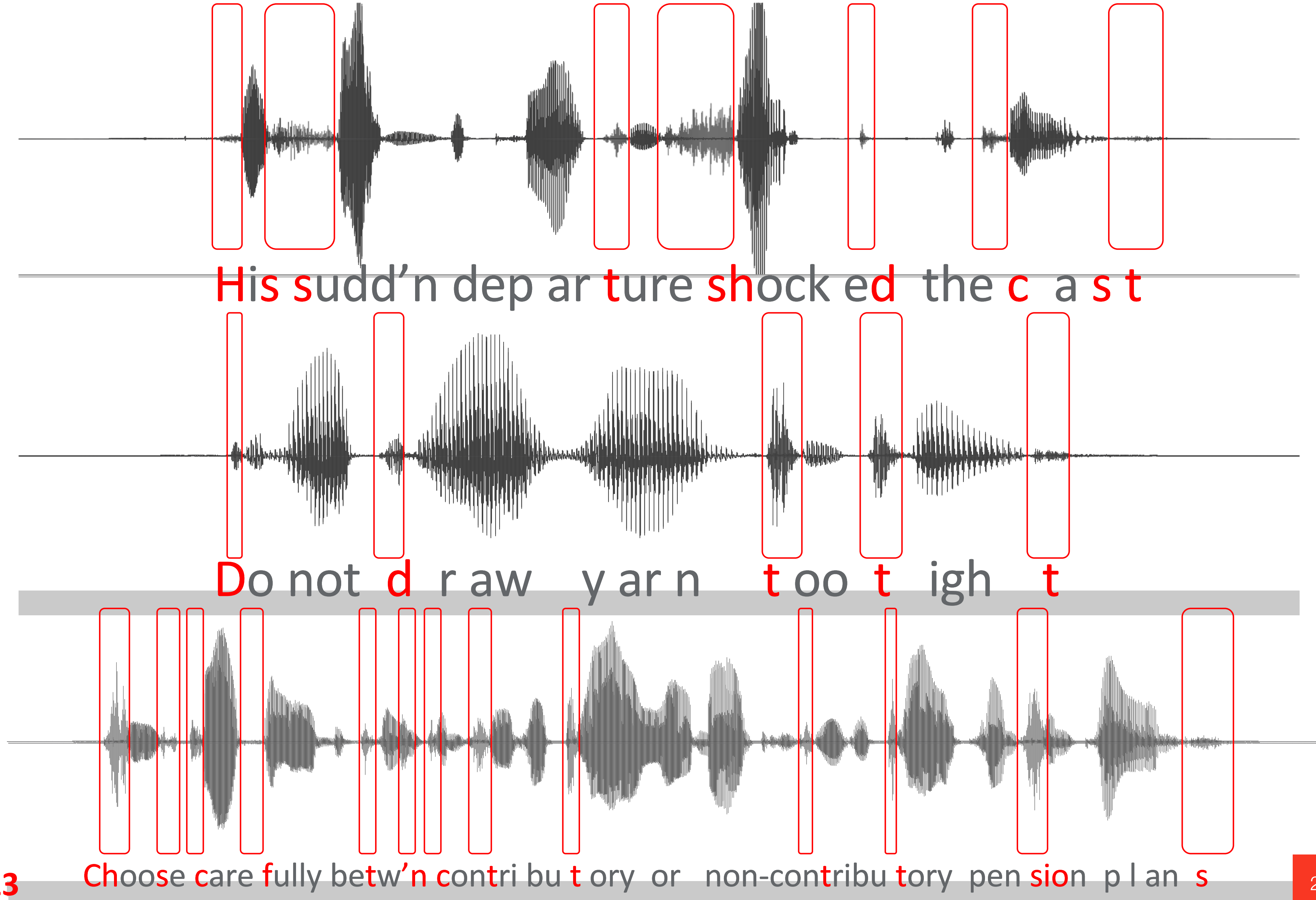
# Vowel Recognition by Tongue Height



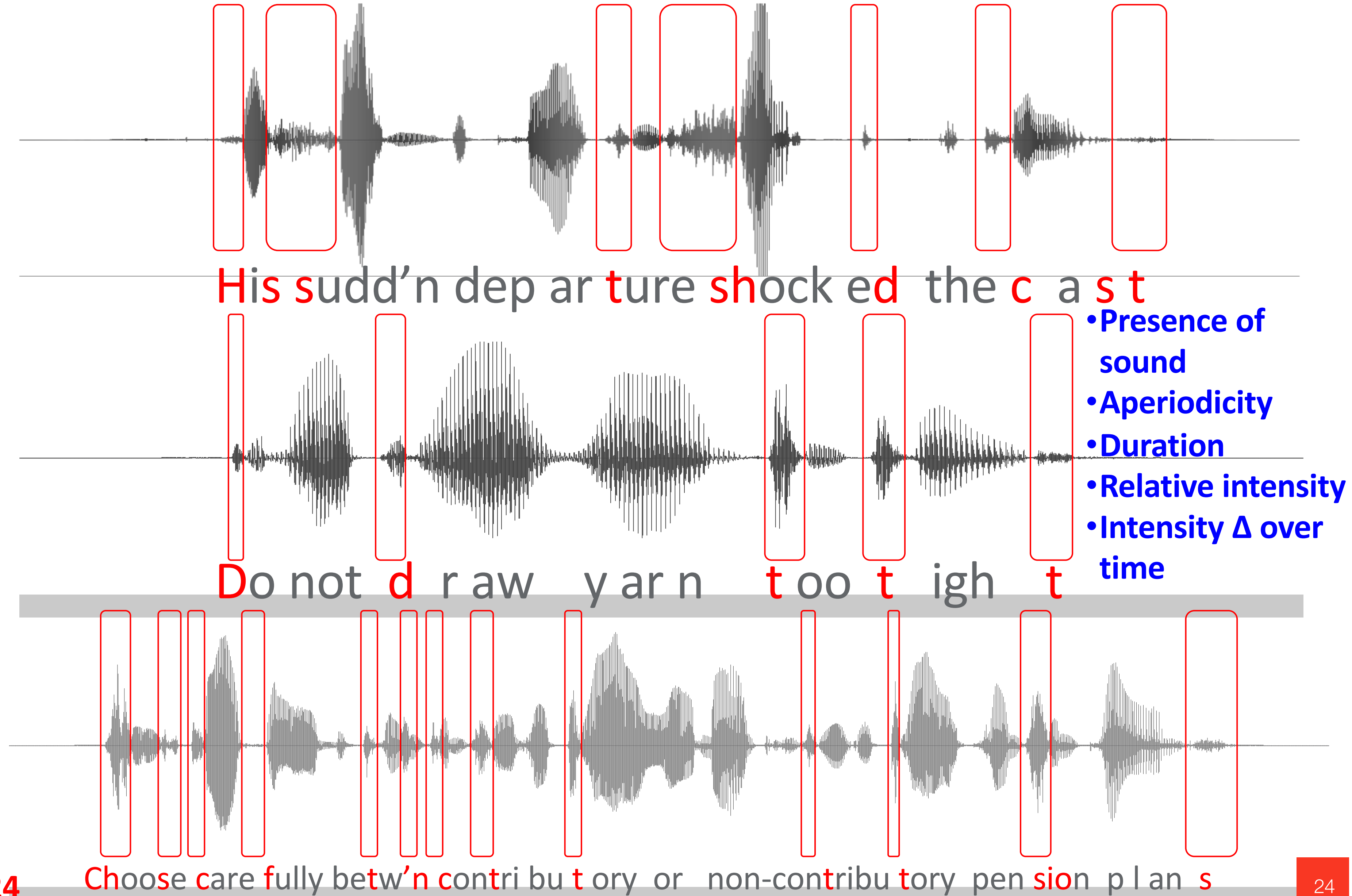



# Frequency Lowering

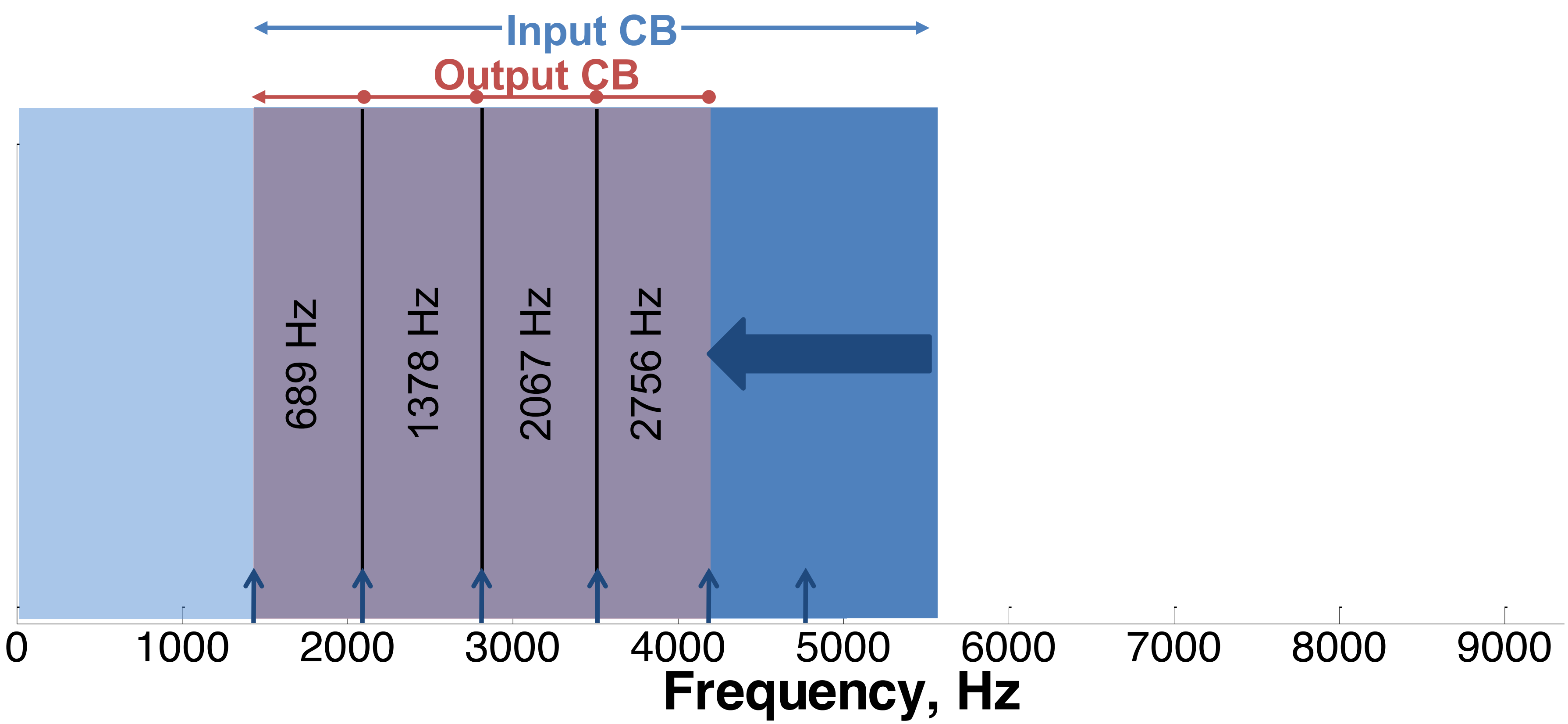
# Frequency Lowering Information



# Frequency Lowering Information



# Nonlinear Freq. Compression (NFC)



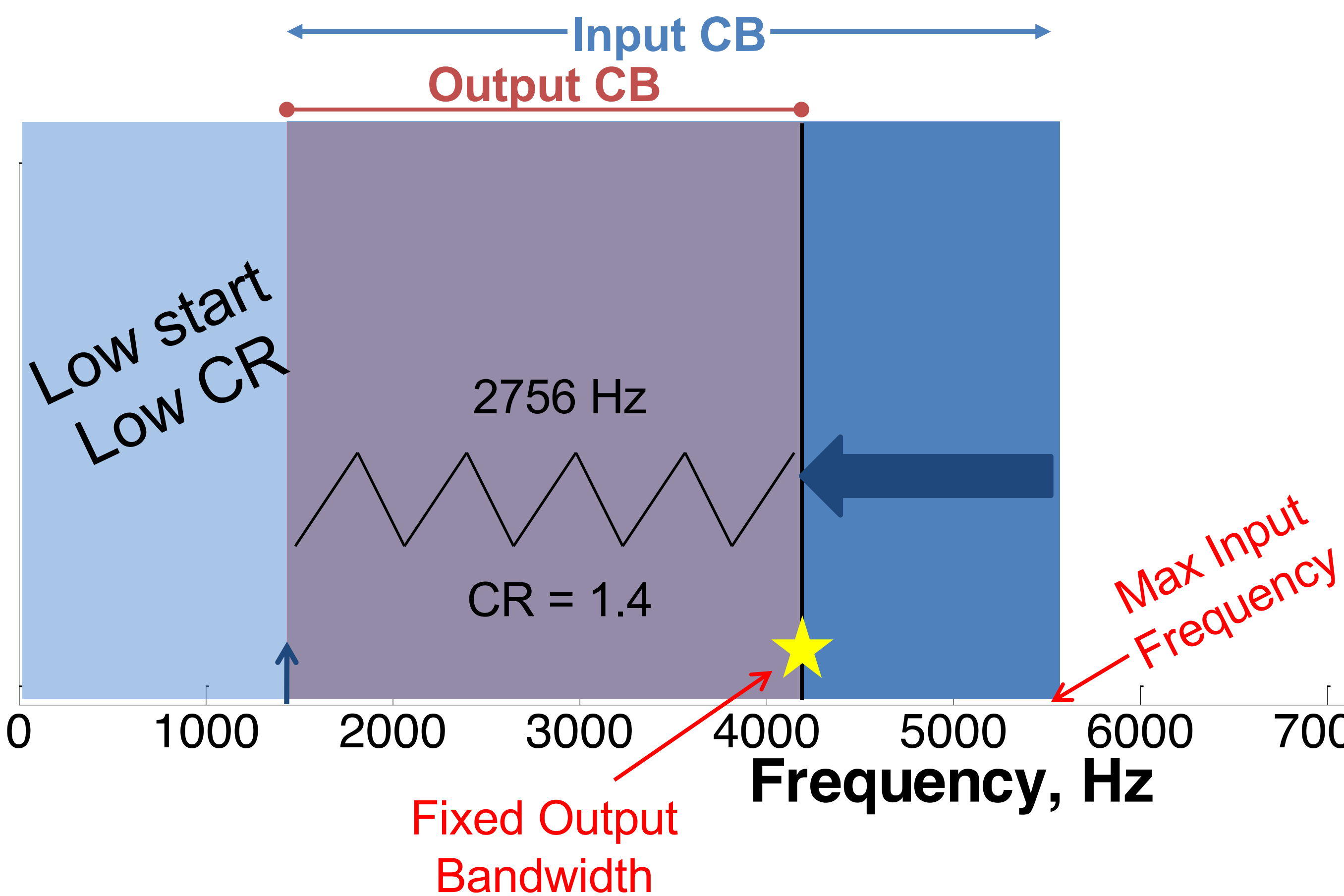
# Maximum Audible Output Freq.

**Start Frequency, Hz**

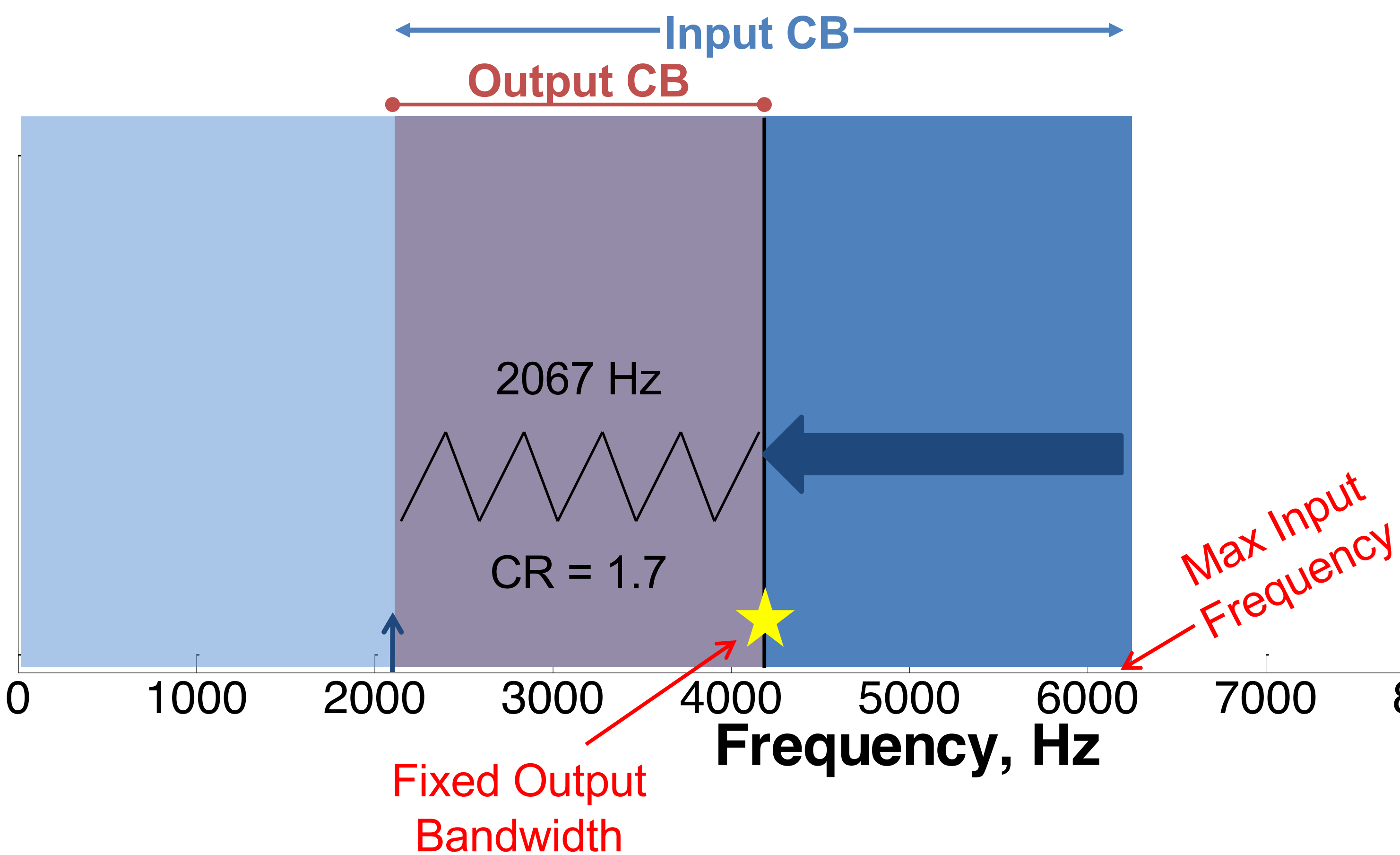
| CR | Output CB | 1378 | 2067 | 2756 | 3445 | 4134 | 4823 |
|---|---|---|---|---|---|---|---|
| (3.4 – 4.6) | 689 | 2067 | 2756 | 3445 | 4134 | 4823 | 5513 |
| (2.0 – 2.5) | 1378 | 2756 | 3445 | 4134 | 4823 | 5513 | 6202 |
| (1.5 – 1.7) | 2067 | 3445 | 4134 | 4823 | 5513 | 6202 | 6891 |
| (1.3 – 1.4) | 2756 | 4134 | 4823 | 5513 | 6202 | 6891 | 7580 |
| | Maximum Input Frequency, Hz | *5513* | *6202* | *6891* | *7580* | *8269* | *8958* |

**Maximum Input Frequency, Hz**

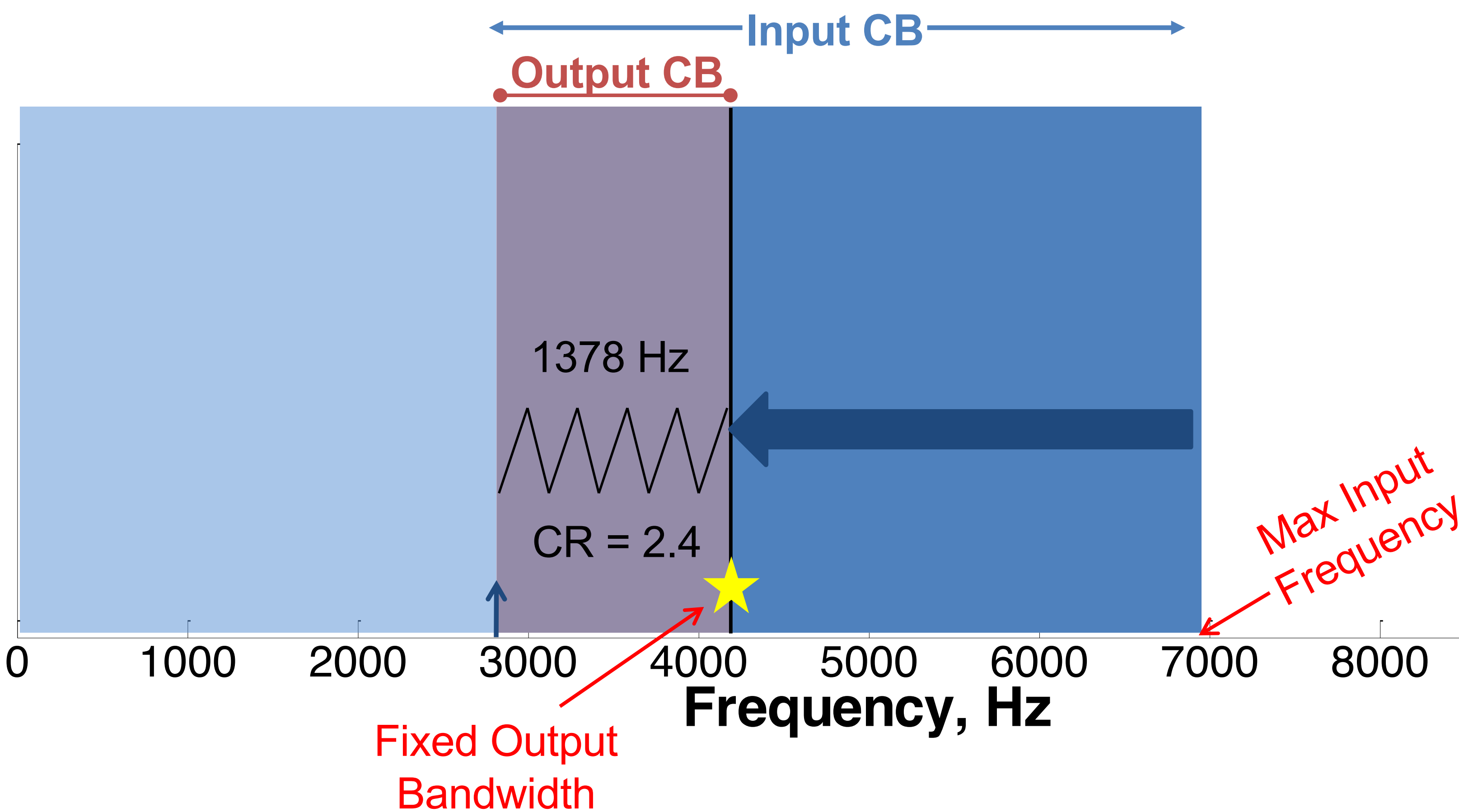
# Ways to re-package information limited to a fixed output bandwidth using NFC



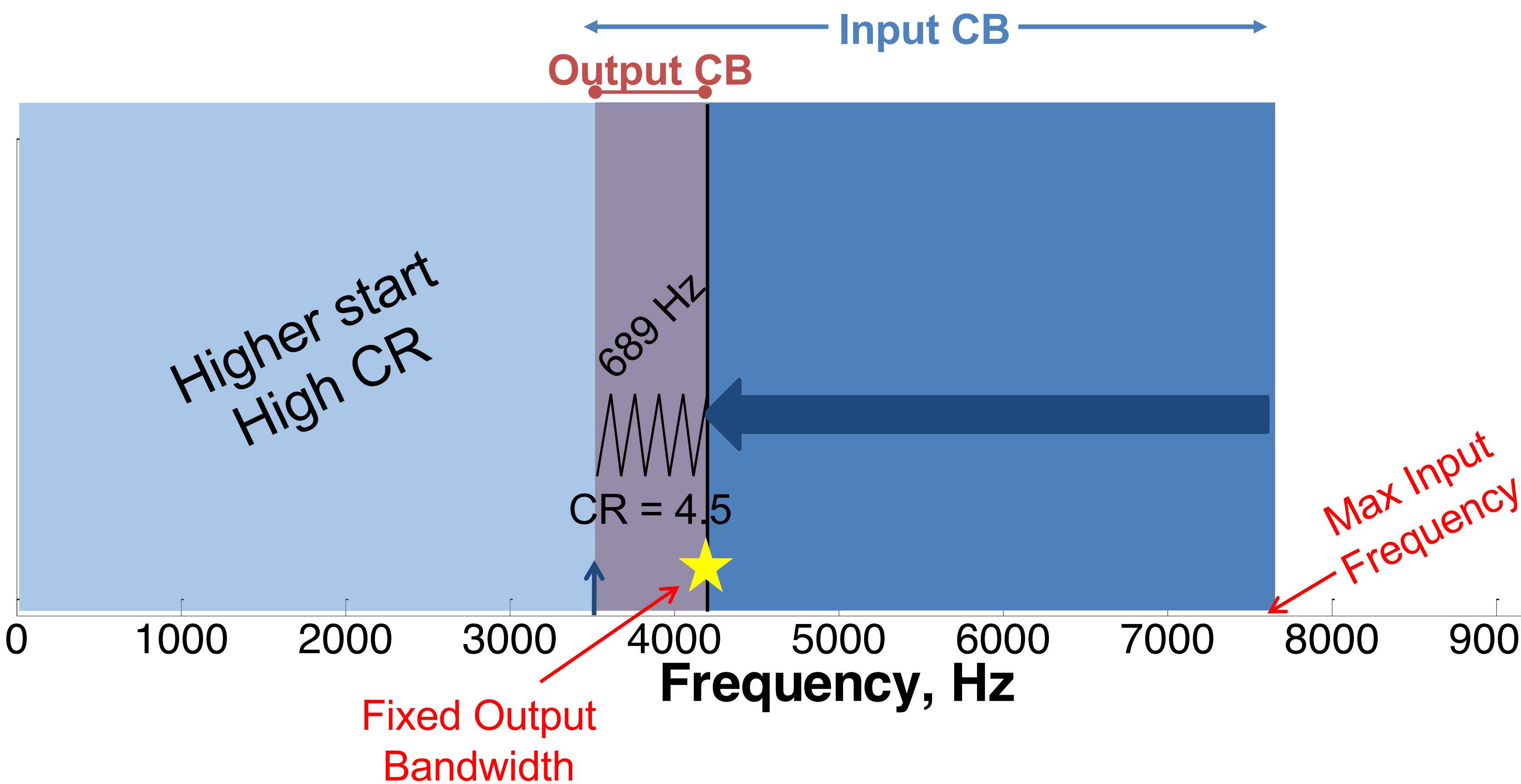
# Ways to re-package information limited to a fixed output bandwidth using NFC



# Ways to re-package information limited to a fixed output bandwidth using NFC



# Ways to re-package information limited to a fixed output bandwidth using NFC



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# Efficiency Measures

1. Convert confusion matrix to information transmitted (IT) in bits

| | p | t | k | b | d | g | f | th | s | sh | v | z | j | ch | m | n | l | r | w | y | SENT | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| p | **36** | 3 | 12 | . | . | 1 | 12 | 3 | 3 | 1 | . | . | . | . | . | . | . | . | . | 1 | 72 | p |
| t | . | **28** | 12 | . | 1 | . | . | 1 | 1 | 1 | . | . | . | 28 | . | . | . | . | . | . | 72 | t |
| k | 14 | 7 | **33** | . | . | . | 8 | 2 | 6 | . | . | . | . | 2 | . | . | . | . | . | . | 72 | k |
| b | 2 | . | 1 | **21** | 6 | 8 | . | 7 | . | . | 20 | . | 1 | 1 | 2 | . | . | 2 | 1 | . | 72 | b |
| d | . | . | . | 7 | **42** | 19 | . | . | . | . | 1 | 2 | . | . | . | 1 | . | . | . | . | 72 | d |
| g | 6 | 3 | 1 | 7 | 4 | **29** | . | 4 | . | . | 2 | 7 | 7 | 1 | . | . | . | . | 1 | . | 72 | g |
| f | 4 | 3 | 3 | . | . | . | **34** | 6 | 17 | 4 | . | . | . | 1 | . | . | . | . | . | . | 72 | f |
| th | . | 1 | . | 10 | 10 | 4 | . | **12** | . | 1 | 23 | 6 | 1 | . | . | 1 | 2 | . | . | 1 | 72 | th |
| s | . | . | 1 | . | . | . | 7 | . | **10** | 53 | 1 | . | . | . | . | . | . | . | . | . | 72 | s |
| sh | . | . | . | . | . | . | 1 | . | . | **69** | . | . | . | 1 | . | . | . | . | 1 | . | 72 | sh |
| v | . | . | . | 8 | 4 | 2 | 2 | 7 | 1 | . | **38** | 5 | 3 | . | . | . | . | 1 | 1 | . | 72 | v |
| z | . | . | . | 1 | . | . | . | 3 | . | 3 | 3 | **22** | 29 | 2 | . | . | . | 6 | . | 3 | 72 | z |
| j | . | 6 | 2 | . | 8 | 4 | . | . | . | . | 2 | . | **46** | 3 | . | . | 1 | . | . | . | 72 | j |
| ch | . | 17 | 1 | . | . | . | . | . | . | . | . | . | . | **54** | . | . | . | . | . | . | 72 | ch |
| m | . | . | . | 1 | . | 1 | . | 4 | . | . | 4 | 3 | 1 | . | **24** | 8 | 10 | 6 | 7 | 3 | 72 | m |
| n | . | . | . | 1 | 3 | . | . | 3 | . | . | 5 | . | 2 | . | 5 | **20** | 11 | 11 | 4 | 7 | 72 | n |
| l | . | . | . | 1 | . | . | . | 6 | . | 1 | 2 | 1 | 1 | . | 1 | 4 | **30** | 12 | 7 | 6 | 72 | l |
| r | . | . | . | 7 | 1 | 2 | . | 2 | 1 | . | 10 | 3 | . | . | . | 3 | 13 | **27** | 2 | 1 | 72 | r |
| w | 1 | . | . | 13 | . | . | . | 4 | . | . | 6 | 2 | . | . | 4 | 3 | 2 | 7 | **29** | 1 | 72 | w |
| y | . | . | . | 1 | 6 | 4 | . | 2 | . | . | 2 | 5 | 8 | . | 1 | 1 | 2 | 4 | 4 | **32** | 72 | y |
| HEARD | 63 | 68 | 66 | 78 | 85 | 74 | 64 | 66 | 39 | 133 | 119 | 56 | 99 | 93 | 37 | 41 | 71 | 76 | 57 | 55 | 1440 | |
| | p | t | k | b | d | g | f | th | s | sh | v | z | j | ch | m | n | l | r | w | y | TOTAL | |

2. $E = \frac{NFC_{(bits)}}{Full\ band_{(bits)}}$ **Efficiency ≠ Improvement (re: No NFC)**

3. *Efficiency* <1.0 indicates where NFC can be improved with experience, training, or alternative signal processing

# Consonants: Male Talker Efficiency

| CR | Output CB | 1378 | 2067 | 2756 | 3445 | 4134 | 4823 |
|---|---|---|---|---|---|---|---|
| (3.4 – 4.6) | 689 | 0.60 | 0.70 | 0.79 | 0.92 | 0.95 | 0.93 |
| (2.0 – 2.5) | 1378 | 0.68 | 0.73 | 0.88 | 0.94 | 0.93 | 0.97 |
| (1.5 – 1.7) | 2067 | 0.71 | 0.83 | 0.90 | 0.96 | 0.95 | 0.96 |
| (1.3 – 1.4) | 2756 | 0.81 | 0.92 | 0.92 | 0.96 | 0.94 | 1.02 |
| Maximum Input Frequency, Hz | | *5513* | *6202* | *6891* | *7580* | *8269* | *8958* |

Column headers (1378–4823): Start Frequency, Hz

- For start freq. ≤ 2756 Hz, ↓ CR = ↑ efficiency
- Efficiency is close 1.0 for start freq. ≥ 3445 Hz

# Consonants: Female Talker Efficiency

| CR | Output CB | Start Frequency, Hz: 1378 | 2067 | 2756 | 3445 | 4134 | 4823 |
|---|---|---|---|---|---|---|---|
| (3.4 – 4.6) | 689 | 0.65 | 0.71 | 0.77 | 0.89 | 0.91 | 0.89 |
| (2.0 – 2.5) | 1378 | 0.76 | 0.74 | 0.83 | 0.90 | 0.94 | 0.90 |
| (1.5 – 1.7) | 2067 | 0.82 | 0.81 | 0.88 | 0.95 | 0.96 | 0.93 |
| (1.3 – 1.4) | 2756 | 0.84 | 0.95 | 0.92 | 0.99 | 0.97 | 0.97 |
| | Maximum Input Frequency, Hz | *5513* | *6202* | *6891* | *7580* | *8269* | *8958* |

- For all start freq., ↓ CR = ↑ efficiency
- Efficiency is close 1.0 only for start freq. ≥ 3445 Hz with CR < 2.0

# Consonant Efficiency Summary

- Male and female **average efficiency** both equal 0.87
- **Affricates** have *efficiency* near 1.0 except for the condition with the lowest start freq. and highest CR
- **Fricatives** have the lowest *efficiency* ($\underline{M}$ = 0.75)
- **Approximants** ($\underline{M}$ = 0.88), **stops** ($\underline{M}$ = 0.84)
- **Nasals** have poor *efficiency* for start freq. ≤ 2067 Hz ($\underline{M}$ = 0.52), and *efficiency* near 1.0 above this
  - Cued by low-frequency formant and anti-formant
- *Efficiency* & response time: Pearson *r* = -0.61

continued

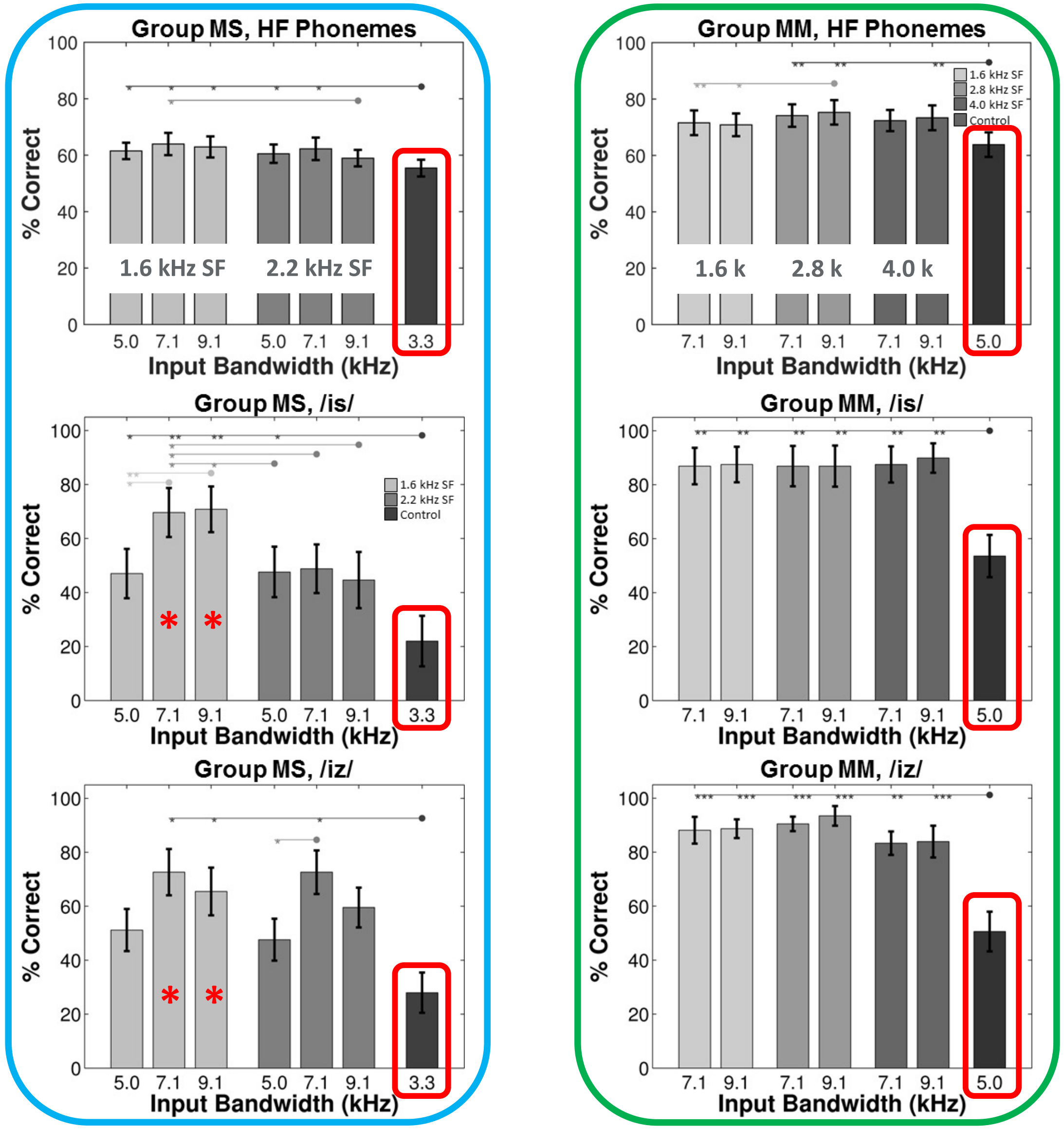
# Vowels: *Efficiency*

| CR | Output CB | Start Frequency, Hz: 1378 | 2067 | 2756 | 3445 | 4134 |
|---|---|---|---|---|---|---|
| (3.4 – 4.6) | 689 | 0.71 | 0.92 | 0.97 | 0.97 | 0.98 |
| (2.0 – 2.5) | 1378 | 0.85 | 0.93 | 0.97 | 0.99 | 0.98 |
| (1.5 – 1.7) | 2067 | 0.93 | 0.98 | 0.98 | 0.99 | 1.00 |
| (1.3 – 1.4) | 2756 | 0.97 | 0.99 | 0.98 | 1.00 | 0.98 |
| | Maximum Input Frequency, Hz | *5513* | *6202* | *6891* | *7580* | *8269* |

- 1378 Hz start freq. with CR ≥ 2.0 have the lowest efficiency, especially for front vowels (0.53)
- For all other conditions, efficiency is close 1.0

Hearing-Impaired Listeners

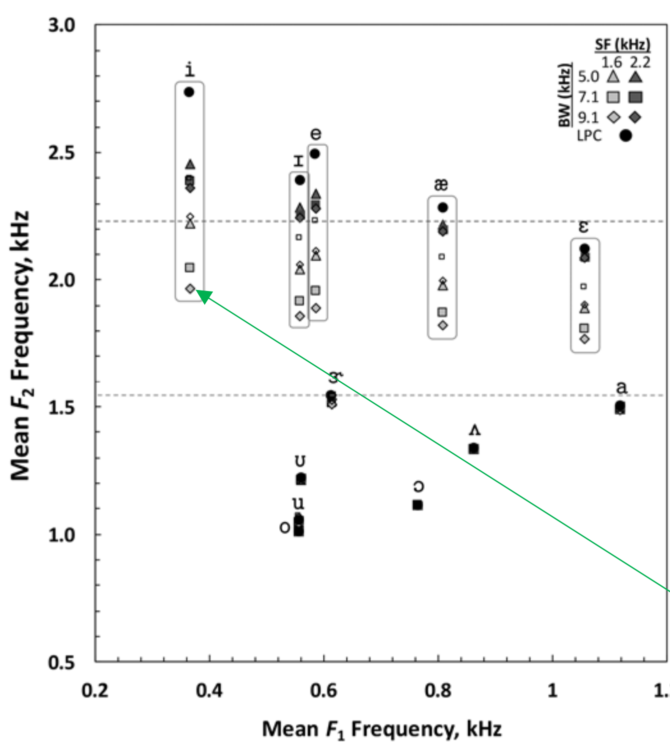
- 2 Groups
  - Moderately-severe (MS)
    - MAOF = 3.3 kHz
  - Mild to moderate (MM)
    - MAOF = 5.0 kHz
- High-Frequency (HF) Phonemes
  - Vowel /i/ followed by 1 of 7 fricatives
  - Female talkers
- Frequency Lowering
  - NFC

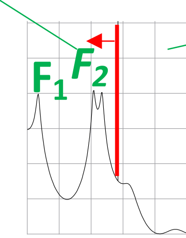


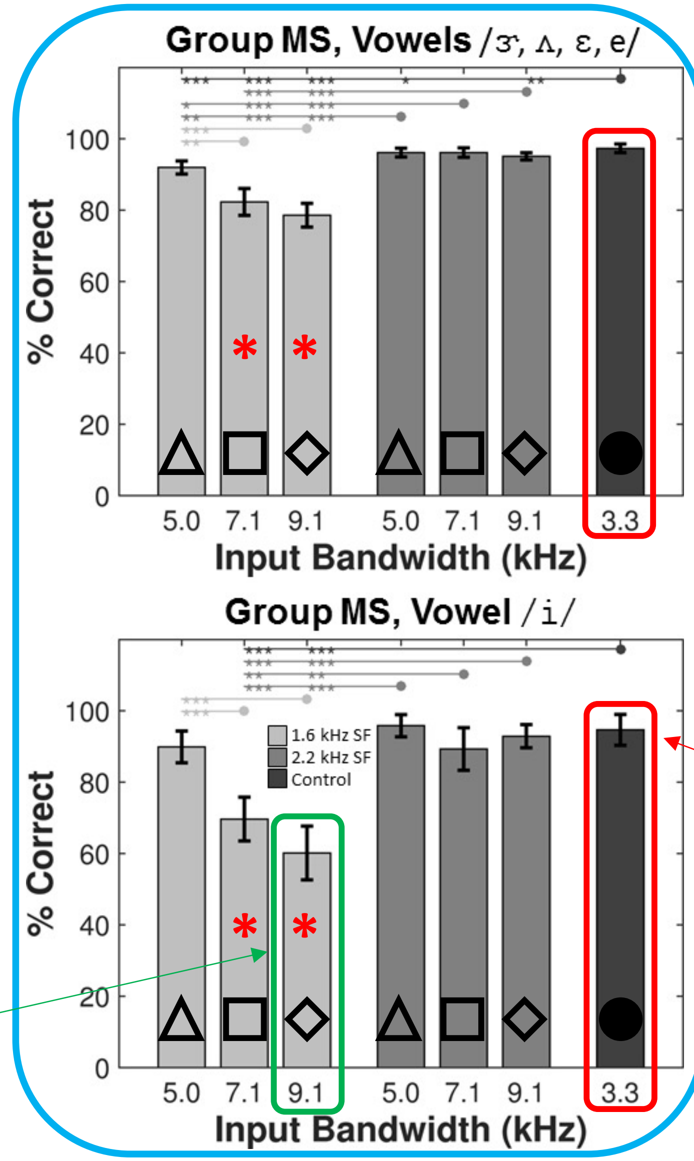

(Alexander, 2016)

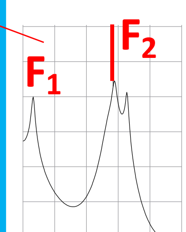
Q4

# Low-start frequencies can be detrimental to vowel perception



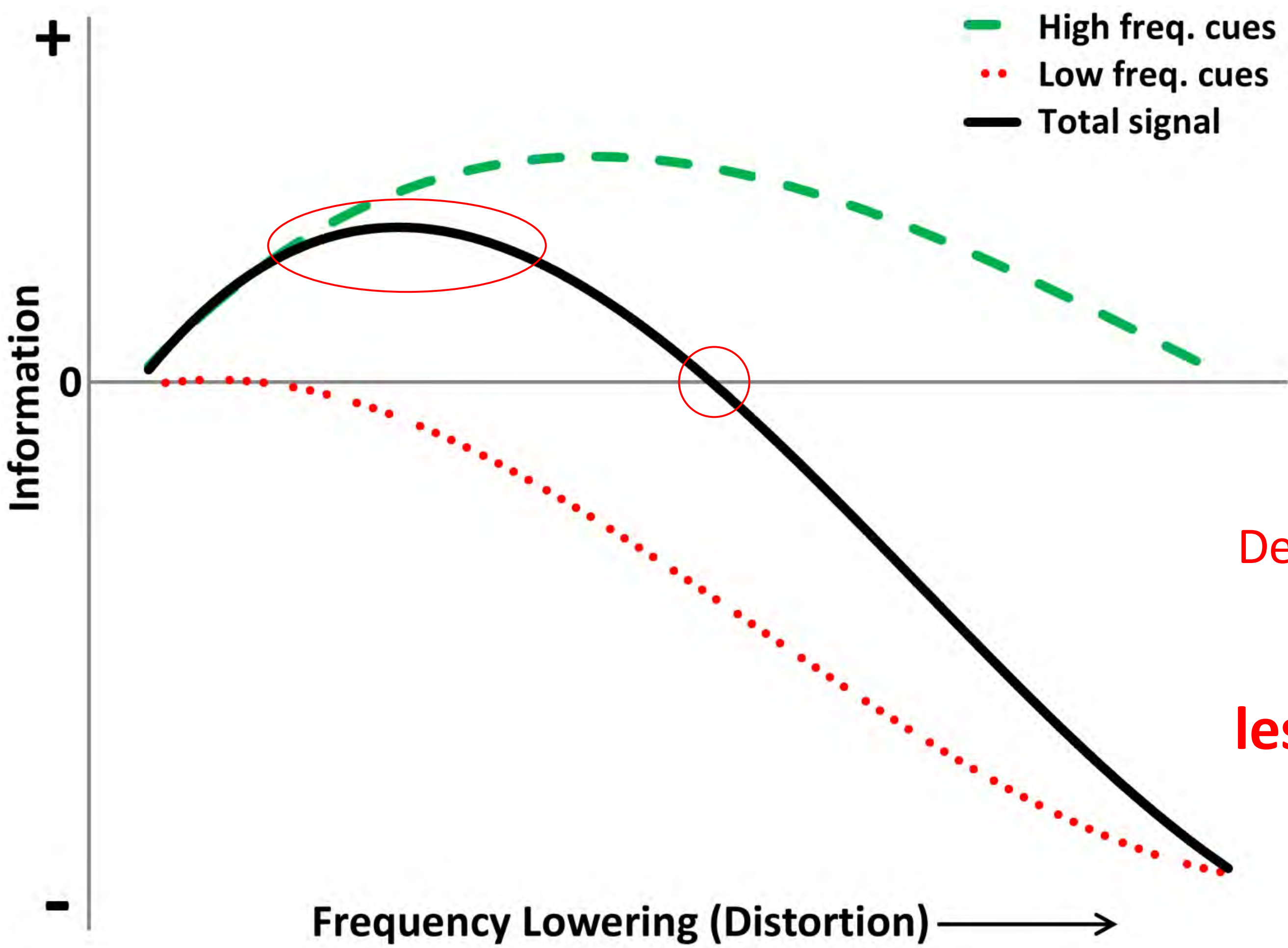




(Alexander, 2016)

Q5

# Information-Theoretic Model




A successful fitting requires **giving the patient more than is taken away**

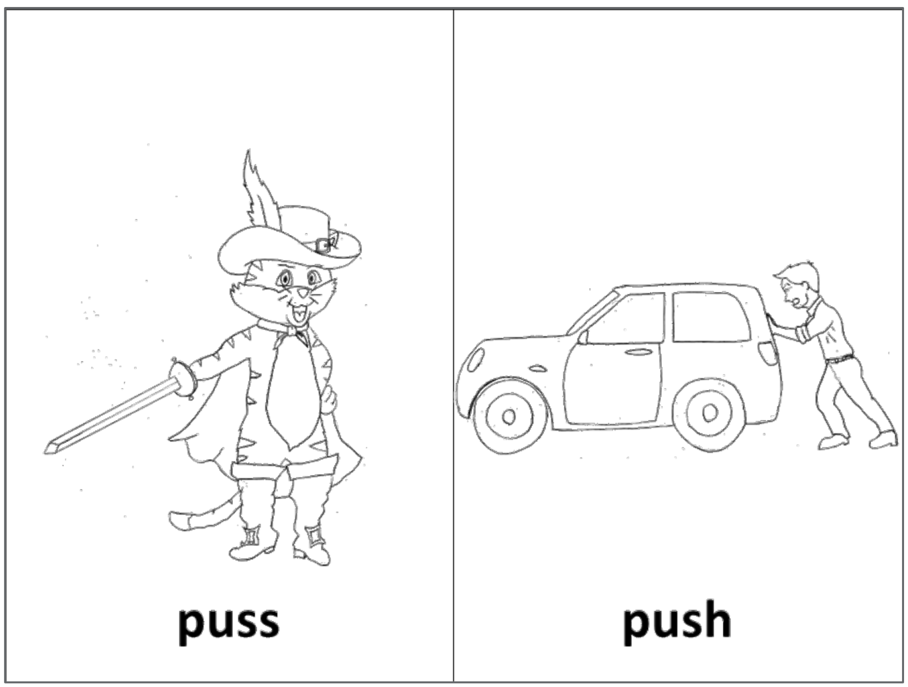
DO NO HARM

Depends on interaction b/w hearing loss & re-coding technique

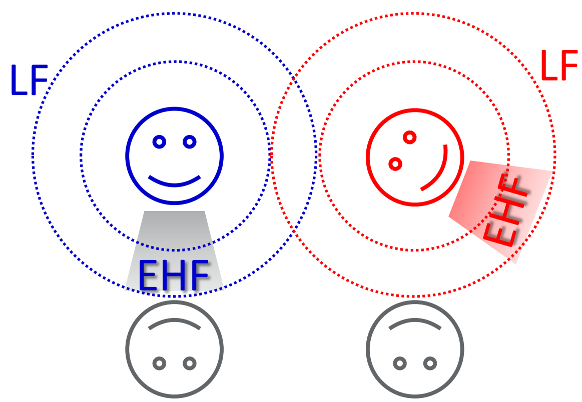
**less can equal more**

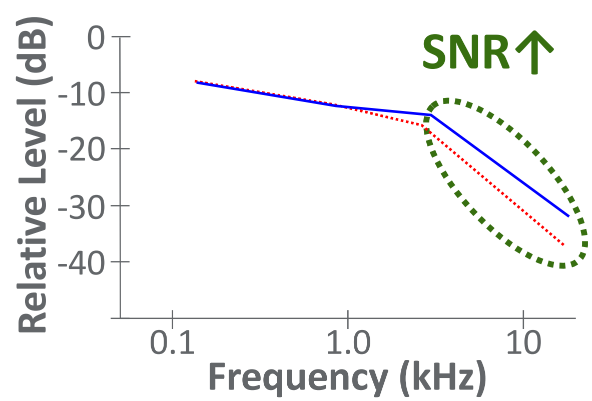
# Speech Tests

- UWO Plurals Test: Glista & Scollie (2012)
- Phoneme Perception Test (PPT): Schmitt et al. (2016)
- ORCA Nonsense Syllable Test: Kuk et al. (2010)
- s-sh Confusion Test: Alexander (2019)




# Head orientation aids high-freq. speech information and spatial cues




Brian Monson, University of Illinois, Urbana-Champaign: https://ahs.illinois.edu/monson

# Finding the right outcomes

- Traditional outcome measures
- Patient report
- Word recognition

- Fricatives (/s/,/z/), affricates, stops (depends on HL)
- Limited context (when the above matter the most)
  - Noise, low predictability and/or new content, low semantic knowledge
- Listening effort/response time
- Spatial processing

# Monday-Morning Summary

- Benefit from extending the bandwidth of speech in normal-hearing listeners — and consequently from frequency lowering in hearing-impaired listeners — is ultimately limited by acoustics as they relate to
    1. one's starting point (the MAOF)
    2. one's ending point (the maximum input frequency of the source signal)
    3. the class of speech sounds
    4. the spectrum and level of background noise
- Use sensitive speech material
- Inquire about ease of listening; plurality, female voices
- Become more informed about the brands you use to better understand how different settings may help or hinder speech understanding

# References

- Figures shown in slides 36 and 37 are reproduced from Alexander, J. M. (2016). "Nonlinear frequency compression: Influence of start frequency and input bandwidth on consonant and vowel recognition," J. Acoust. Soc. Am., 139, 938-957 with the permission of the Acoustical Society of America continuED®

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