Current Perspectives on Noise-Induced Hearing Loss: A framework and recent developments in hearing loss prevention

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Stephenson and Stephenson Research and Consulting

Introduction

- The primary goal of Hearing Loss Prevention (a.k.a. Hearing Conservation):
  - Reduce the incidence and prevalence of hearing trouble
    - Incidence: New cases during a time period
    - Prevalence: Total cases at a point in time

- Harm

  Disadvantageous change

- Hazard

  Agent or event capable of causing harm

- Risk

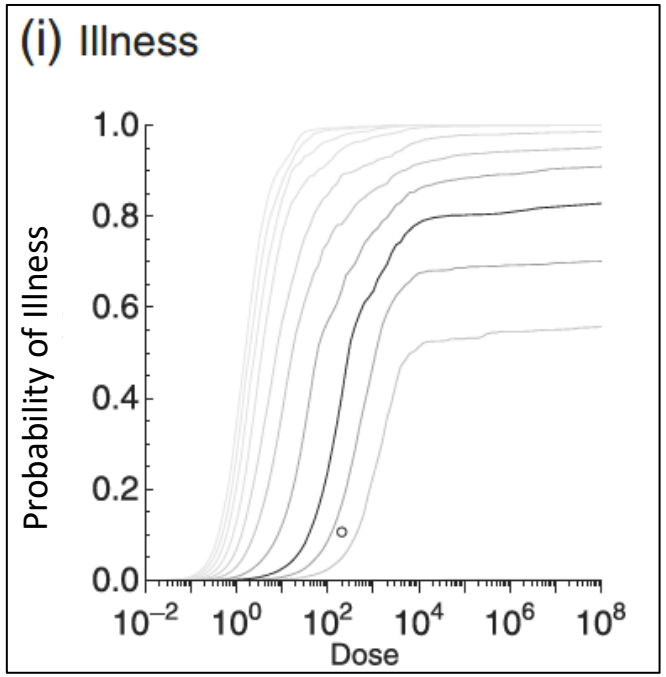
  Probability of harm, given exposure magnitude

- Mitigation

  Strategy to reduce risk

After Deiters et al. book chapter in Alessio & Marron (2024)

Harm, Hazard, Risk, Mitigation



Teunis et al. 2010; Image credit: Wikimedia commons

Harm

- What are we trying to prevent?
  - Important
    - A difference isn't a difference unless it makes a difference
    - "Wild-type human" vs. animal models
  - Measurable
    - While alive
    - Reliably
    - Quickly for large scale

- Example definitions
  - Fowler (1942)
    - Any interference with speech audibility in quiet
    - Complicated
    - Speech Intelligibility Index
    - False alarms at best HLs
  - Based on average threshold
    - Frequency combinations (kHz)
      - 0.5, 1, 2
      - 0.5, 1, 2, 3
      - 0.5, 1, 2, 4
      - 1, 2, 3, 4
      - 2, 3, 4
      - 3, 4, 6
    - Ear combinations
      - Better, worse, combined, composite

After Deiters et al. book chapter in Alessio & Marron (2024)

Harm

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  - Measurable
    - While alive
    - Reliably
    - Quickly for large scale

- Example definitions
  - Individual thresholds
    - Any threshold in any ear worse than some limit

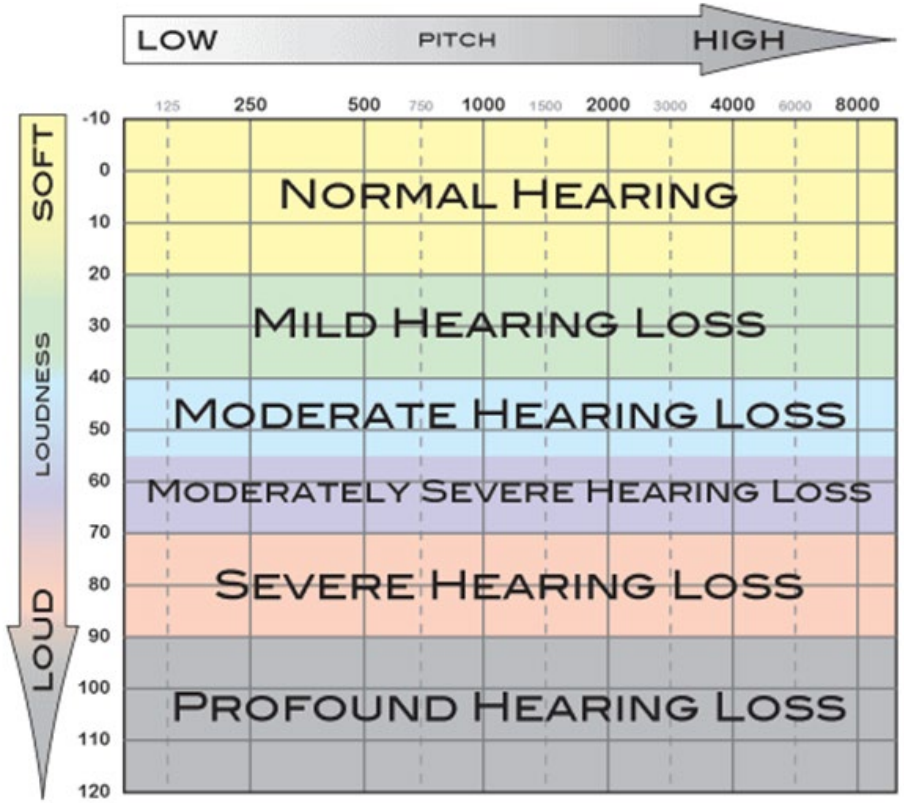

Image from nationalhearingtest.org

Harm

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  - Important
    - A difference isn't a difference unless it makes a difference
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    - While alive
    - Reliably
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- Example definitions
  - Individual thresholds
    - Labels are problematic for general public
      - Can describe configuration
      - Based on averages, but applied to individual thresholds

Table 2

Scale of Hearing Impairment.
(Modified from Goodman, 1965).

Average Hearing Threshold Level in dB (re: 1969 ANSI)	Hearing Loss Label
-10-15	Normal Hearing
16-25	Slight Hearing Loss
26-40	Mild Hearing Loss
41-55	Moderate Hearing Loss
56-70	Moderately Severe Hearing Loss
71-90	Severe Hearing Loss
91 -	Profound Hearing Loss

Clark (1981)

Harm

- How well do these approaches work?
  - Sensitivity
    - Proportion of known cases detected
  - Specificity
    - Proportion of known NON-cases detected
  - Positive Predictive Value
    - Probability of a correct detection
    - Specificity & prevalence
  - Negative Predictive Value
    - Probability of a correct rejection
    - Sensitivity & prevalence

$$\text{Sensitivity} = \frac{\text{True Positives}}{\text{True Positives} + \text{False Negatives}}$$

$$\text{Specificity} = \frac{\text{True Negatives}}{\text{True Negatives} + \text{False Positives}}$$

Audiometric indicator result	Hearing trouble result: Hearing trouble	No hearing trouble	Total
Positive	**A** (True Positive)	B (False Positive)	T Test Positive
Negative	C (False Negative)	**D** (True Negative)	T Test Negative
	T Hearing Trouble	T No hearing trouble	Total

Deiters et al., 2022; NHANES N = 15,172; [Excellent, Good] vs. [Little, Moderate, Lot of Trouble, Deaf]

Harm

- How well do these approaches work?
  - Sensitivity
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  - Positive Predictive Value
    - Probability of a correct detection
    - Specificity & prevalence
  - Negative Predictive Value
    - Probability of a correct rejection
    - Sensitivity & prevalence

$$PPV = \frac{True\ Positives}{True\ Positives + False\ Positives}$$

$$NPV = \frac{True\ Negatives}{True\ Negatives + False\ Negatives}$$

Hearing trouble result

Audiometric indicator result	Hearing trouble	No hearing trouble	Total
Positive	**A** (True Positive)	B (False Positive)	$T_{\text{Test Positive}}$
Negative	C (False Negative)	**D** (True Negative)	$T_{\text{Test Negative}}$
	$T_{\text{Hearing Trouble}}$	$T_{\text{No hearing trouble}}$	Total

Deiters et al., 2022; NHANES N = 15,172; [Excellent, Good] vs. [Little, Moderate, Lot of Trouble, Deaf]

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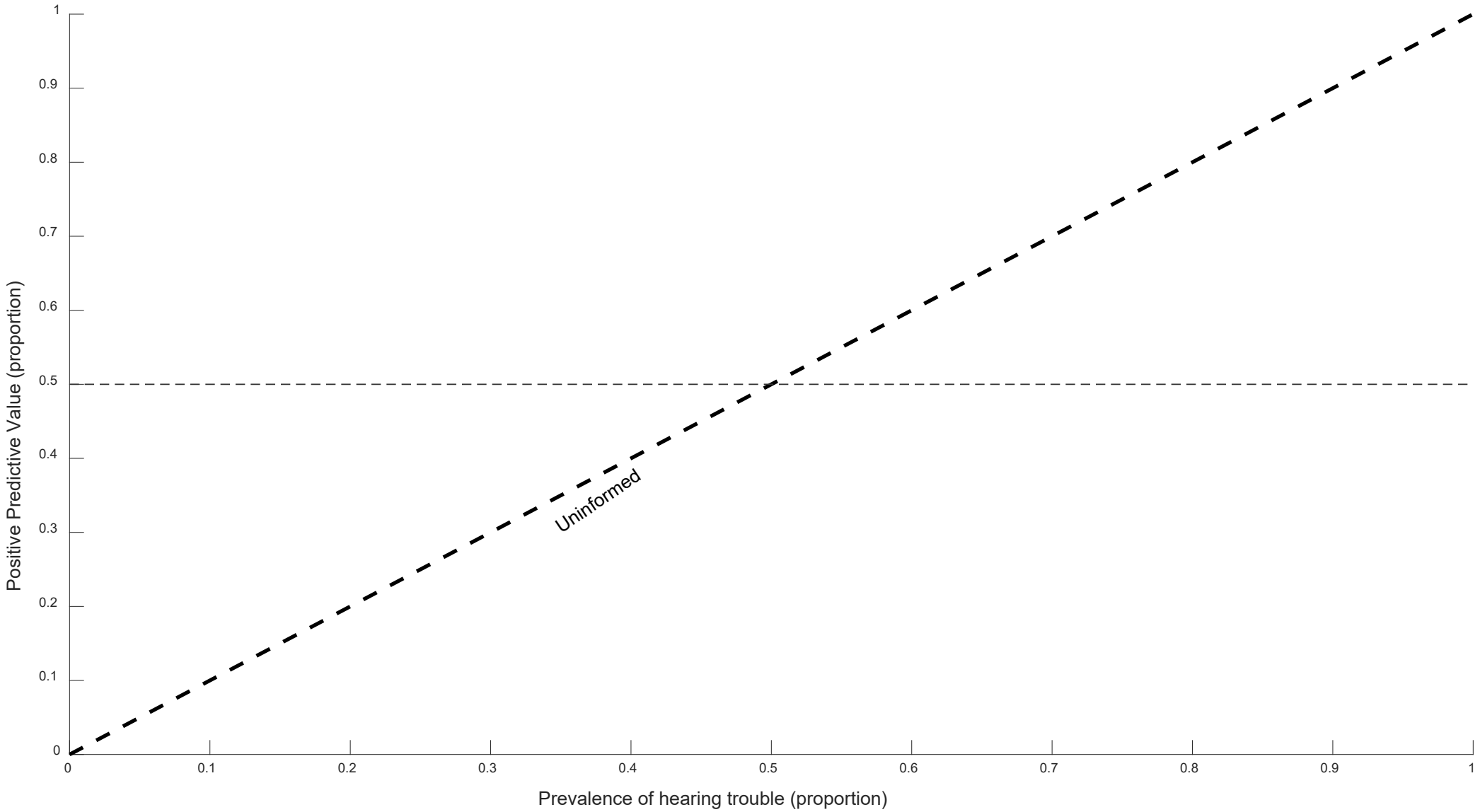
Positive Predictive Value



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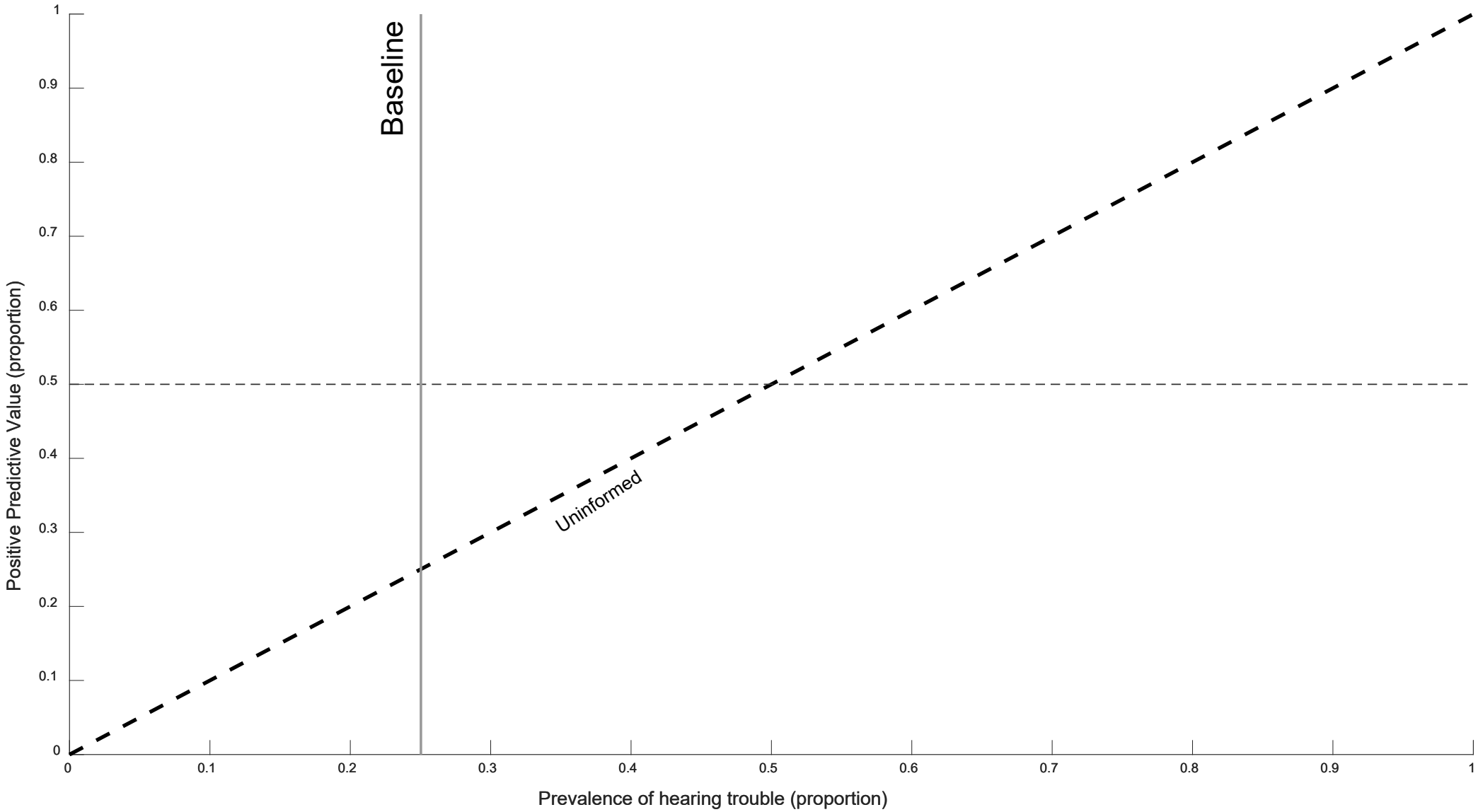

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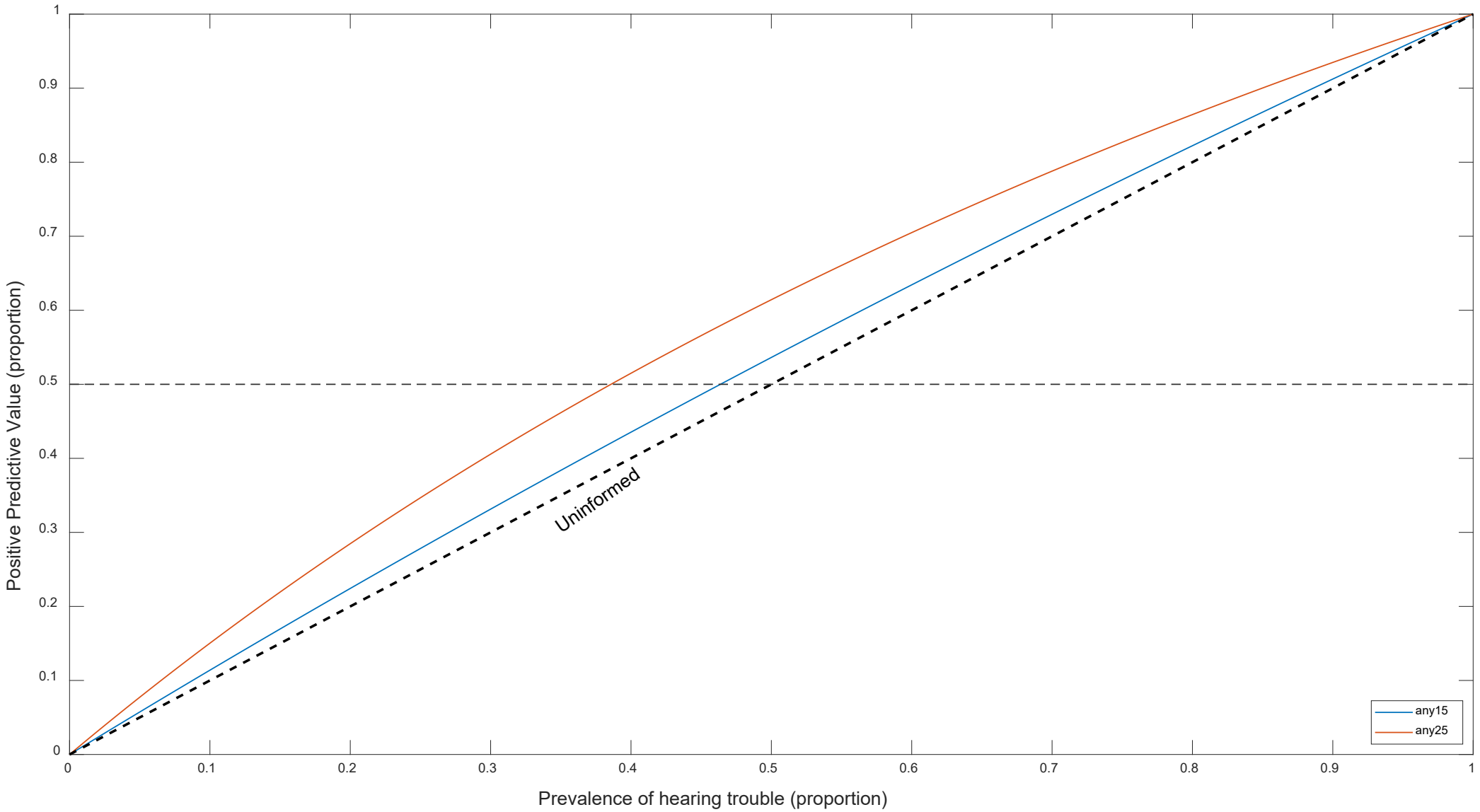

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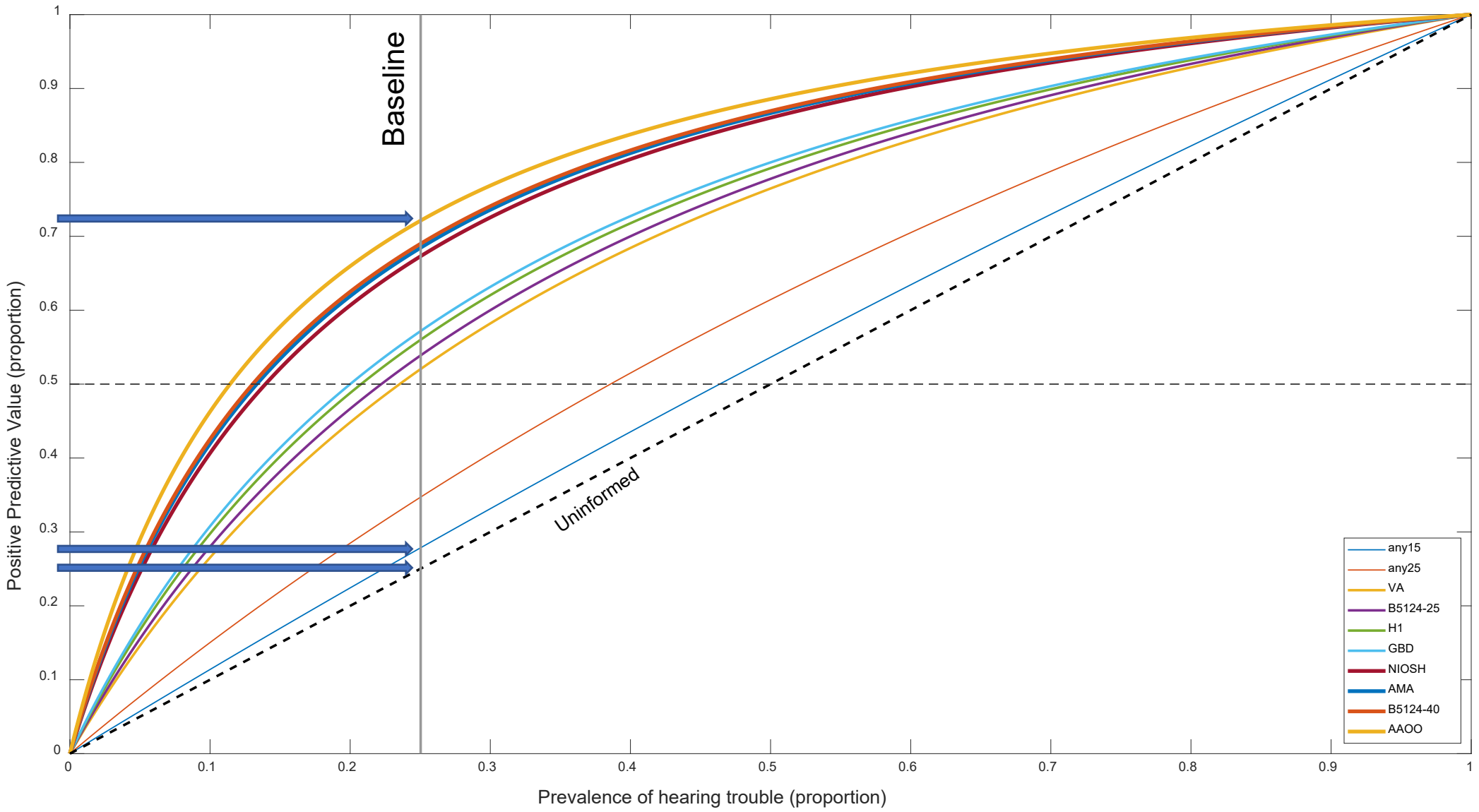
Positive Predictive Value



Deiters et al., 2022; NHANES N = 15,172; [Excellent, Good] vs. [Little, Moderate, Lot of Trouble, Deaf]

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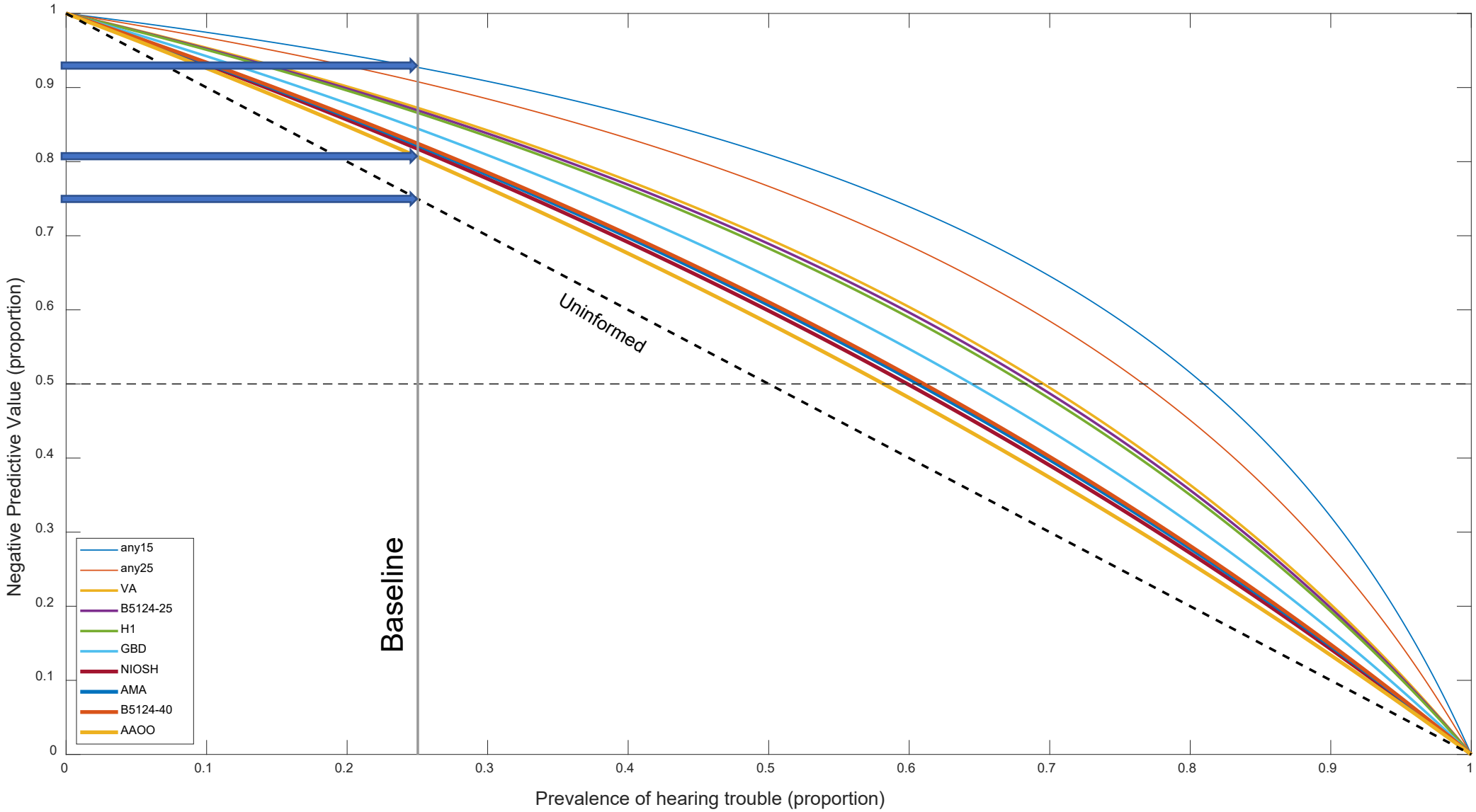
Negative Predictive Value



Deiters et al., 2022; NHANES N = 15,172; [Excellent, Good] vs. [Little, Moderate, Lot of Trouble, Deaf]

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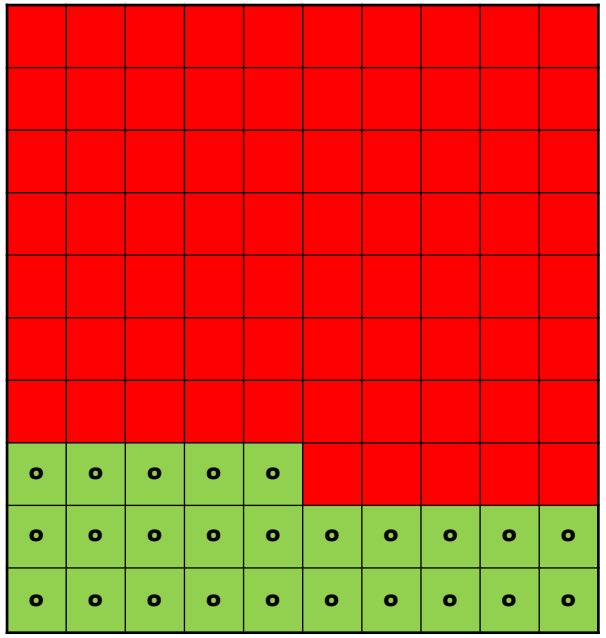
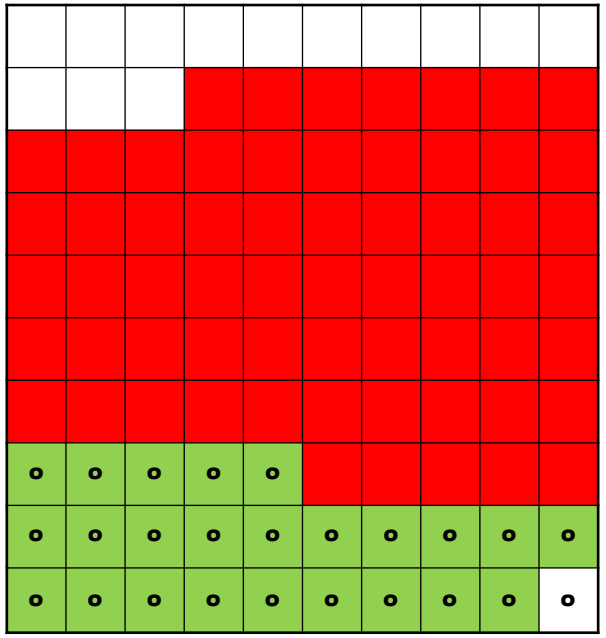
Overall evaluations

What is our appetite for being wrong?



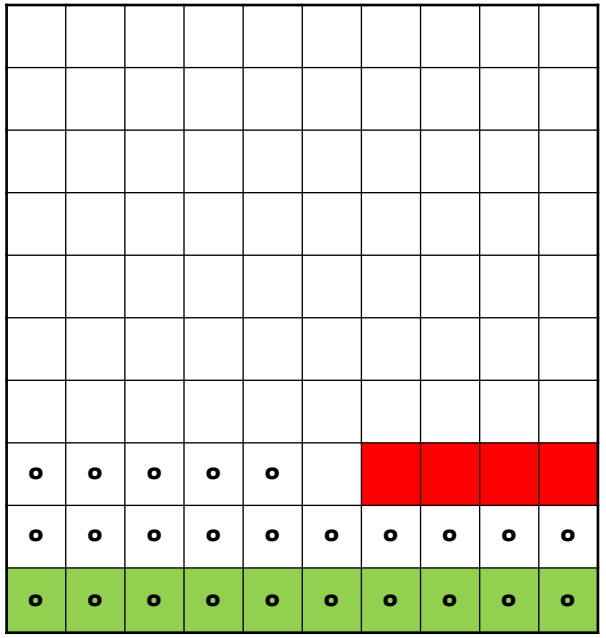
Uninformed: Everyone

25% correct



Any threshold > 15 dB HL

37% correct



AMA

81% correct

°	False negative - individual with hearing trouble incorrectly identified as not having hearing trouble
°	True positive – individual with hearing trouble correctly identified as having hearing trouble
	True negative – individual with no hearing trouble correctly identified
	False positive – individual with no hearing trouble incorrectly identified as having hearing trouble

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Additional definitions

- Short-term sensitivity
  - TTS 2 minutes after end (TTS_2)
  - 15 to 25 dB
  - Military operations
- Cochlear synaptopathy
  - TTS_2 > 50 dB
  - Residual damage after threshold recovery
- Eardrum rupture
- Speech-in-noise
  - Auditory v. Linguistic factors
  - Binary scoring
- Neurocognitive damage
    - Blunt impact, Blast
  - Tinnitus
  - Amyloid beta proteins
  - Decision speed and accuracy
- Educational outcomes
  - Reading
  - Math
  - Science
- Performance degradation
  - Other safety outcomes
  - Mission effectiveness

After Deiters et al. book chapter in Alessio & Marron (2024)

Hazard

- Agent or event capable of causing harm
  - Risk factor
- Capable ≠ Certain
- Exposure: Magnitude × Time

Examples:

- Excessive noise
- Age-related
- Head/Neck injuries
- Ototoxic chemicals
  - Prescription v. other
  - Smoking
  - Organic solvents
- Ear infections
- Inflammation

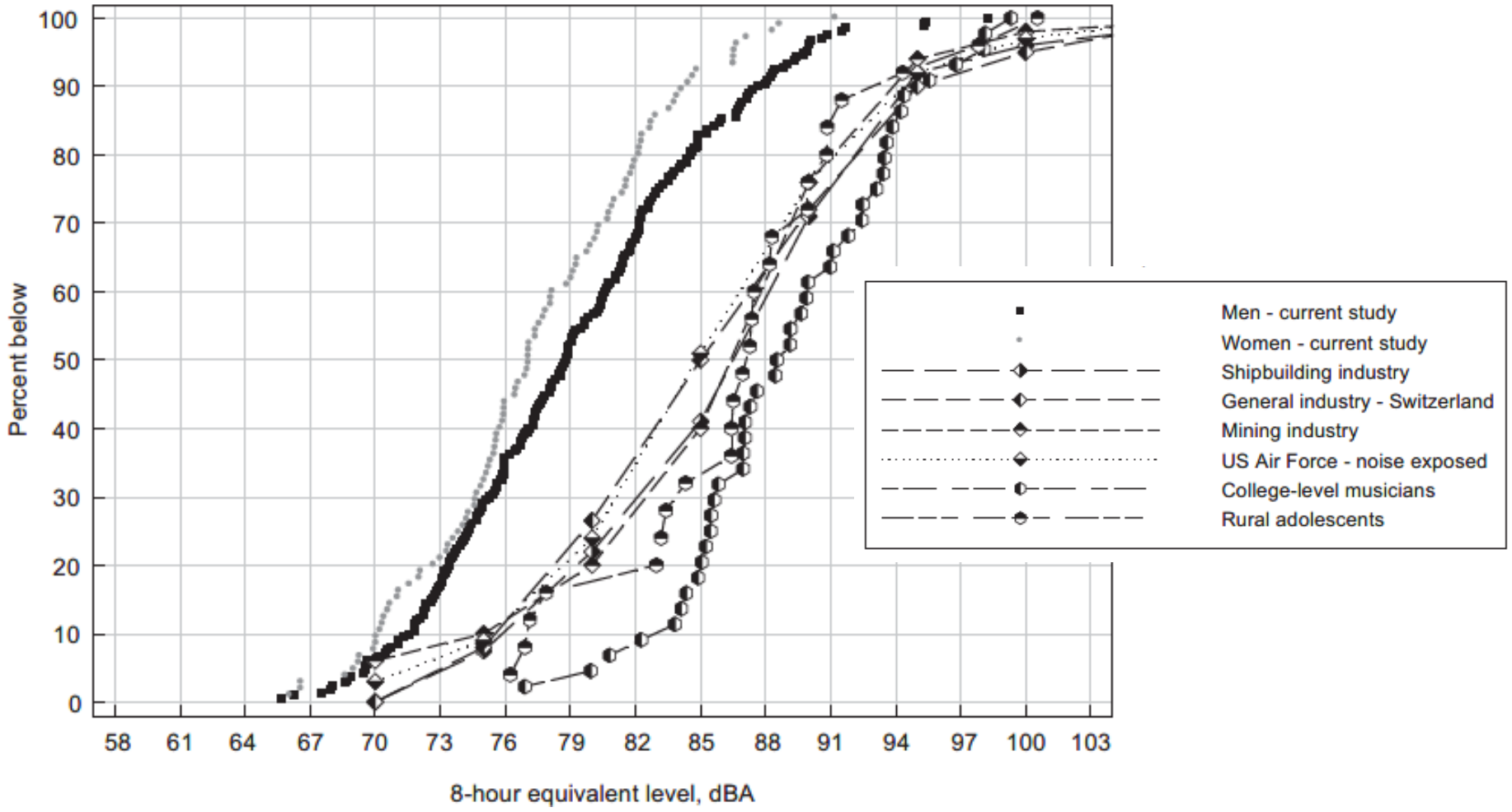
After Deiters et al. book chapter in Alessio & Marron (2024)

Noise

- Continuous
  - Metabolic/oxidative stress
  - Typical noise in daily life
  - Excess risk (Intersociety v. NIOSH)
- Sequential
  - Different exposures in series
  - Effective quiet
    - Below this level, noise does not interfere with recovery from temporary threshold shift
- Impulsive
  - Metabolic/oxidative stress
  - Mechanical strain
  - Impulse: Combustion
  - Impact: Collision
- Mixed/simultaneous
  - Impulsive plus continuous

Noise

- Daily life versus occupational time-weighted averages



Flamme et al. (2012); N = 286, 8.37 person-years

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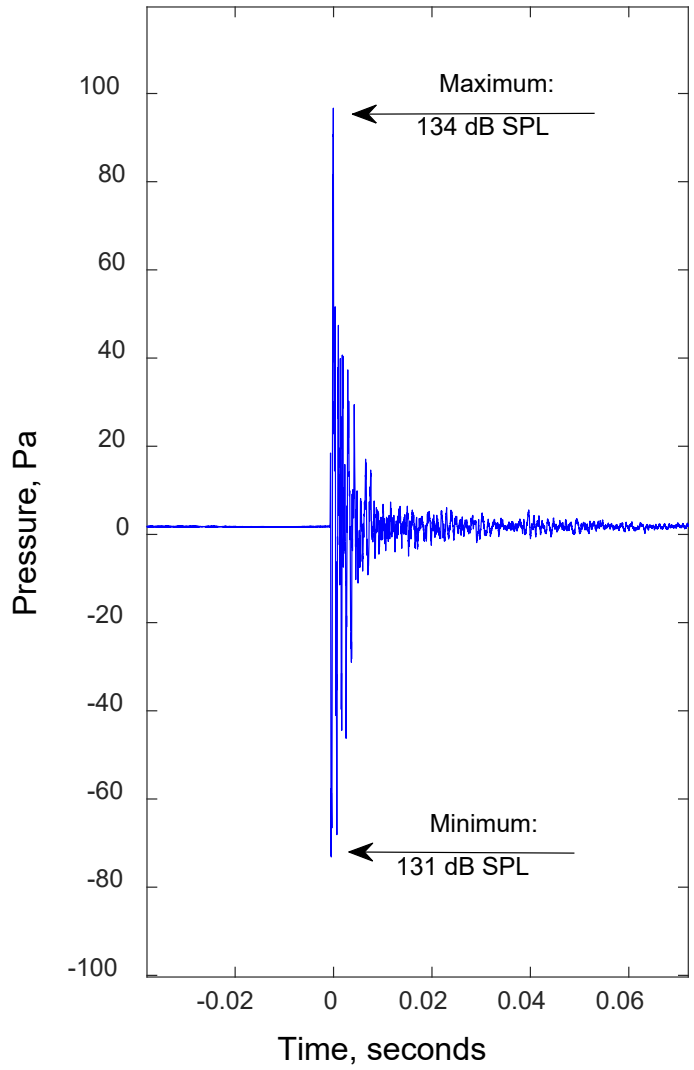
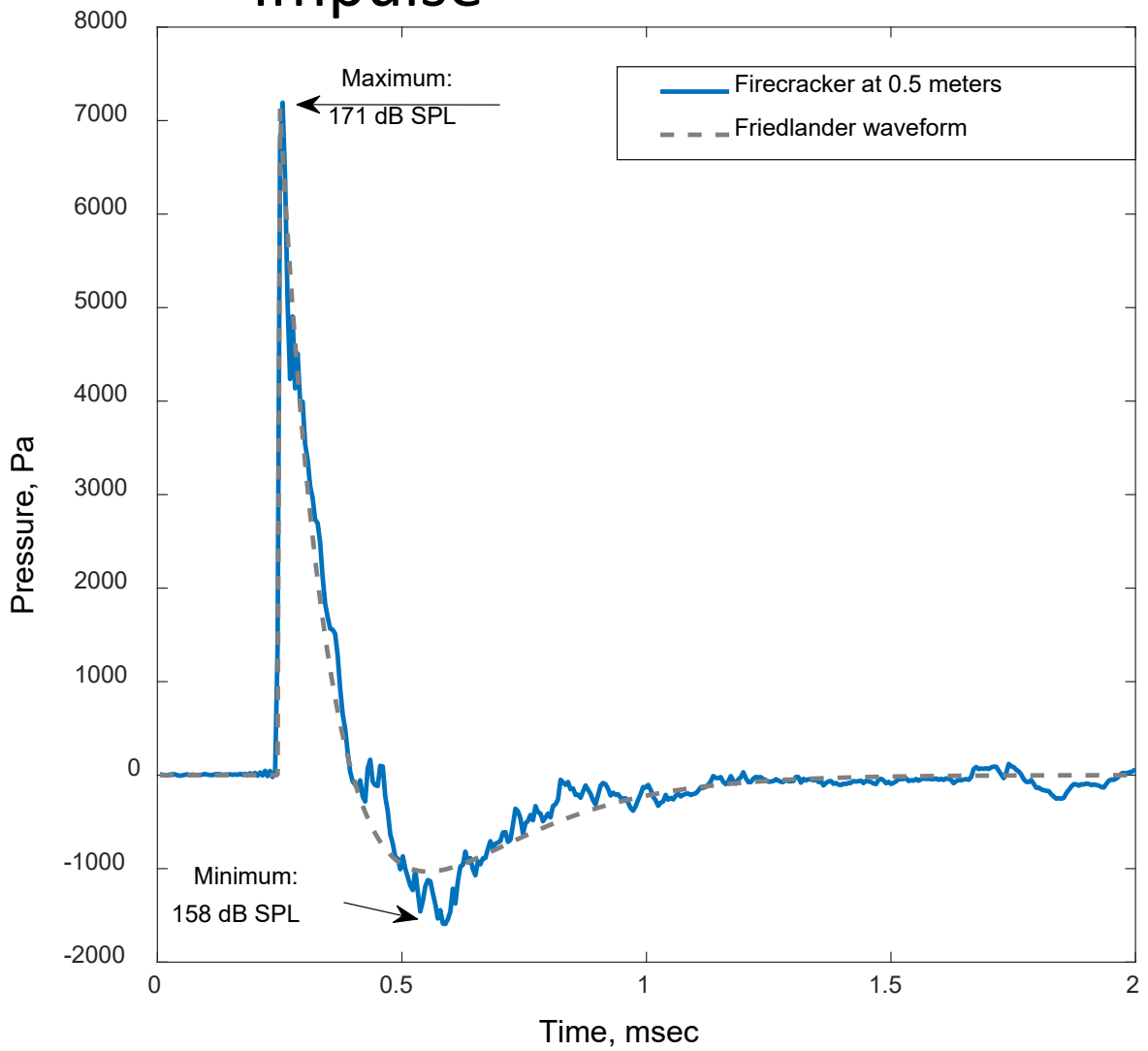
Noise

- Impact



- Impulse



Flamme & Murphy (2022), in Meinke et al. (2022), The Noise Manual, 6th Edition

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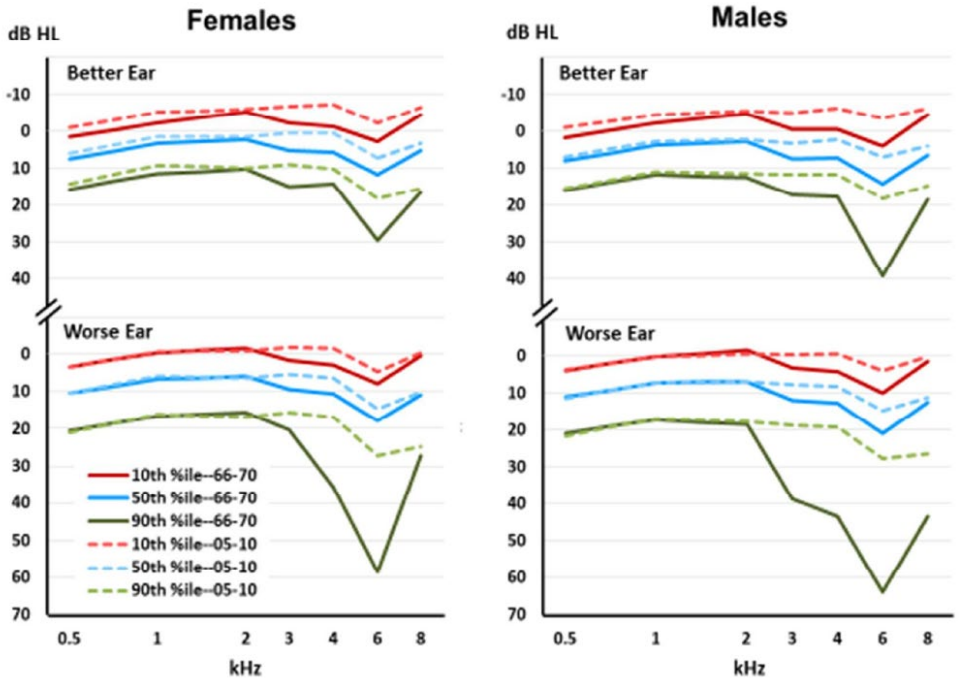
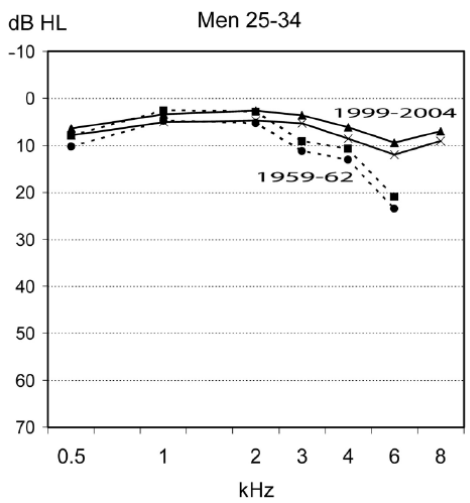
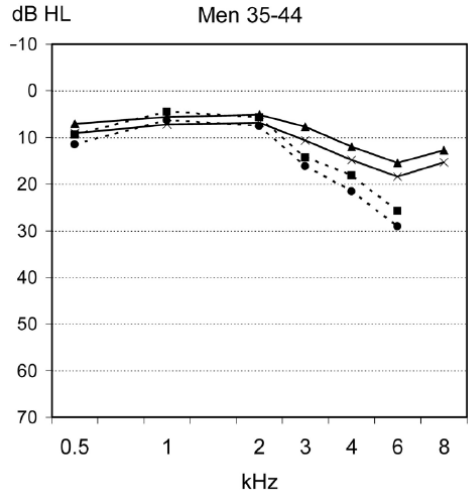
Age-related

- Age-related changes as “background noise”
  - Public health
- Senescence + unmeasured exposures
  - Biology changes slowly
- In the U.S., hearing has improved over the last few decades.
  - Changed exposure and/or mitigation
  - Hidden opportunities







Hoffman et al., 2010, 2019,

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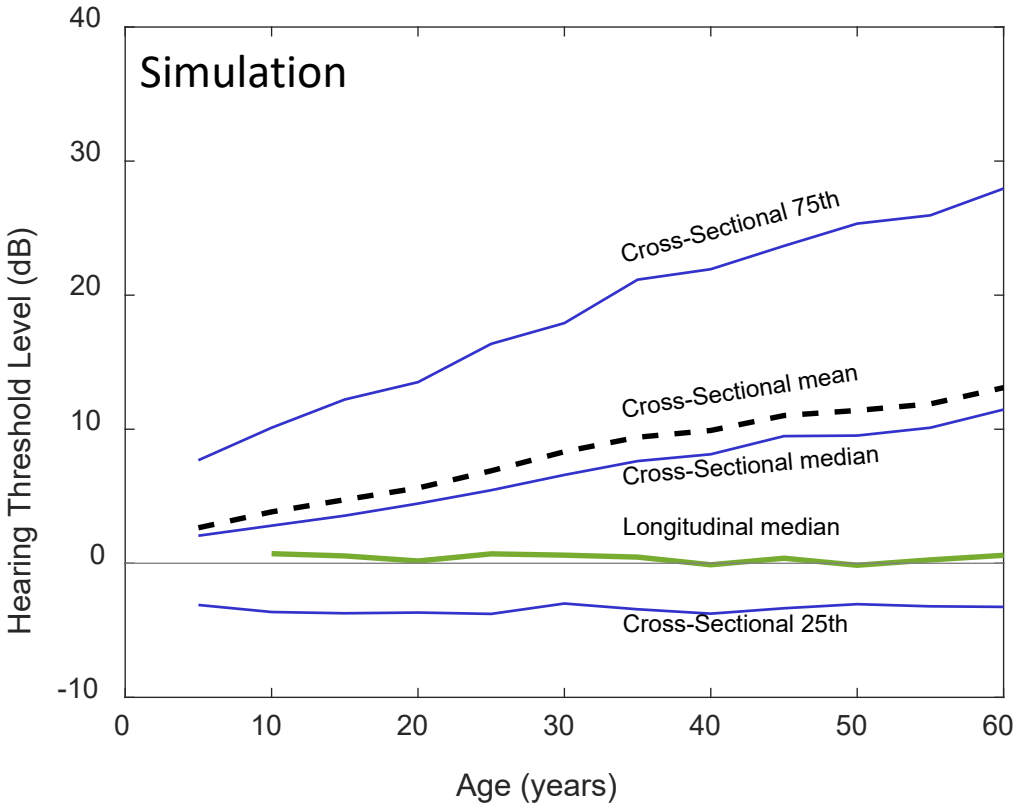
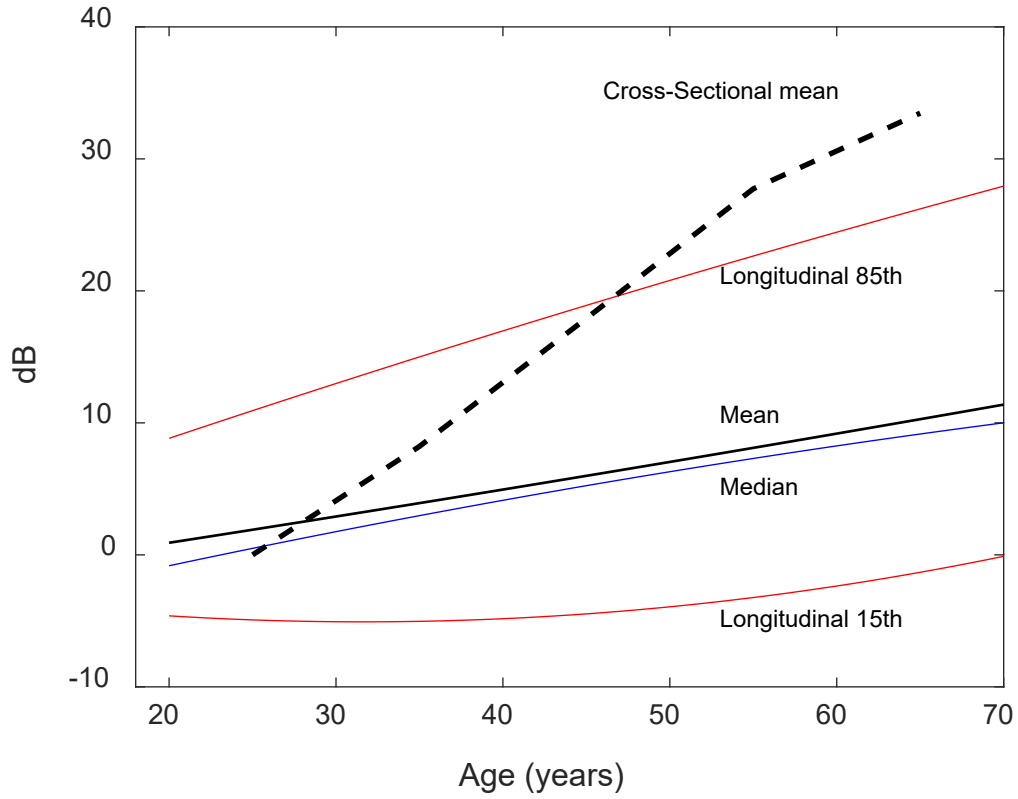
Longitudinal changes vs. Cross-sectional trends

- Longitudinal changes are slower than suggested by cross-sectional trends





Flamme, 2024 & unpublished occupational database analyses (N = 28,660 baselines; test N = 70,134)

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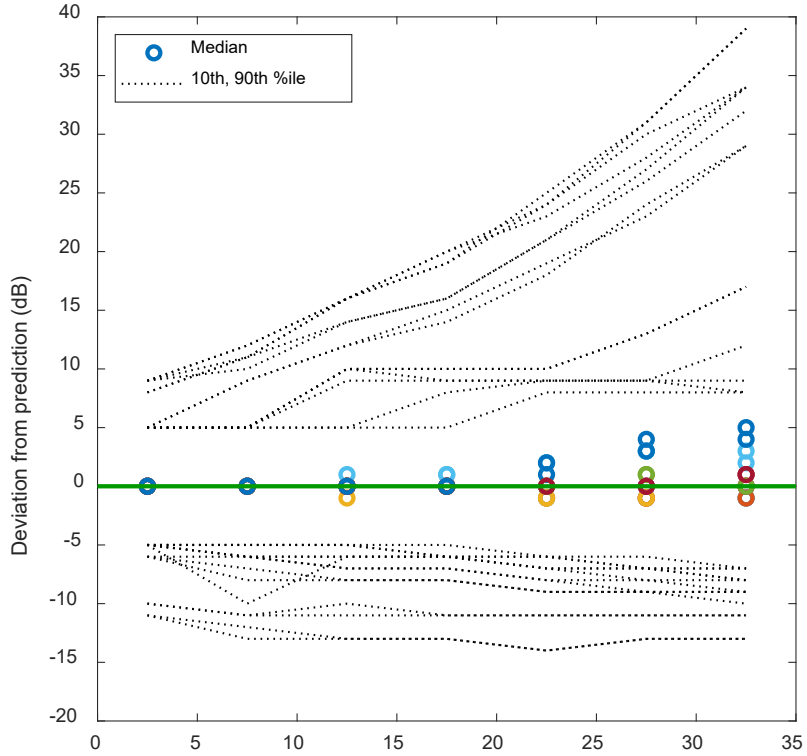
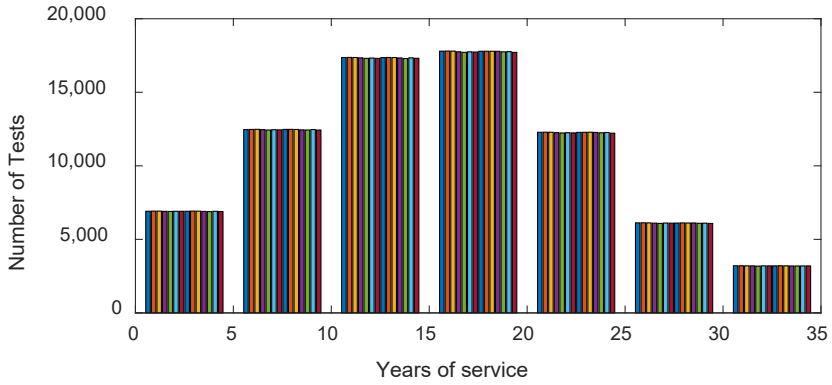
Age-related

- Population-based 25th percentile trend is similar to the median trend
- Asymmetry around median
  - Exposure
  - Health conditions
  - Susceptibility





Analyses of FDNY data

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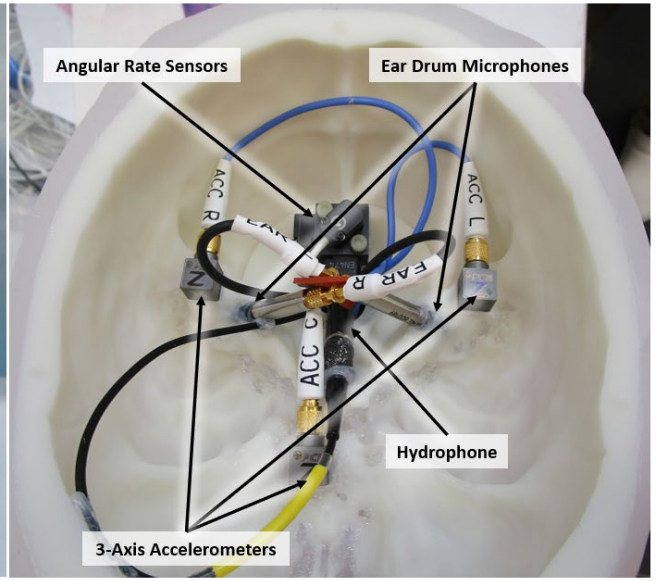
Head and neck injury

- Outcomes
  - Hearing sensitivity
    - With or without skull fracture
    - Closed- or open-head
  - Tinnitus
  - Neurocognitive symptoms
- Modes
  - Blunt force
    - Head impact
    - Fall
    - Motor vehicle accident
  - Blast
    - Small arms discharge
    - Explosions

- New instrumentation
  - Acoustic
  - Acceleration
    - Bone/tissue conduction
  - Hydrophone
    - Pressure waves through brain

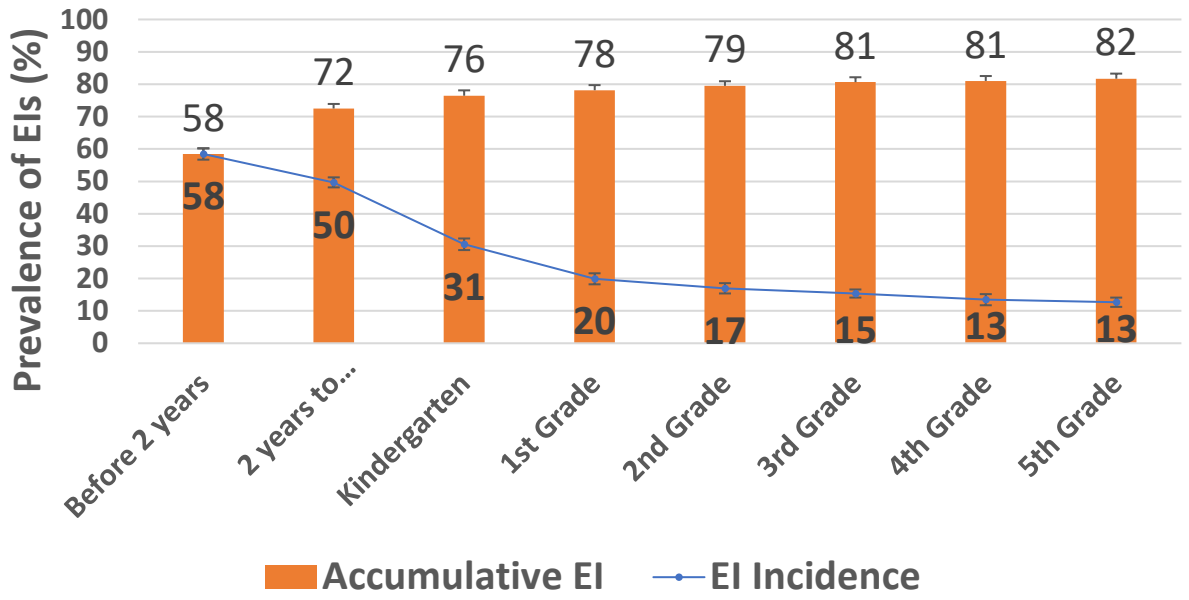
Phantom Exterior

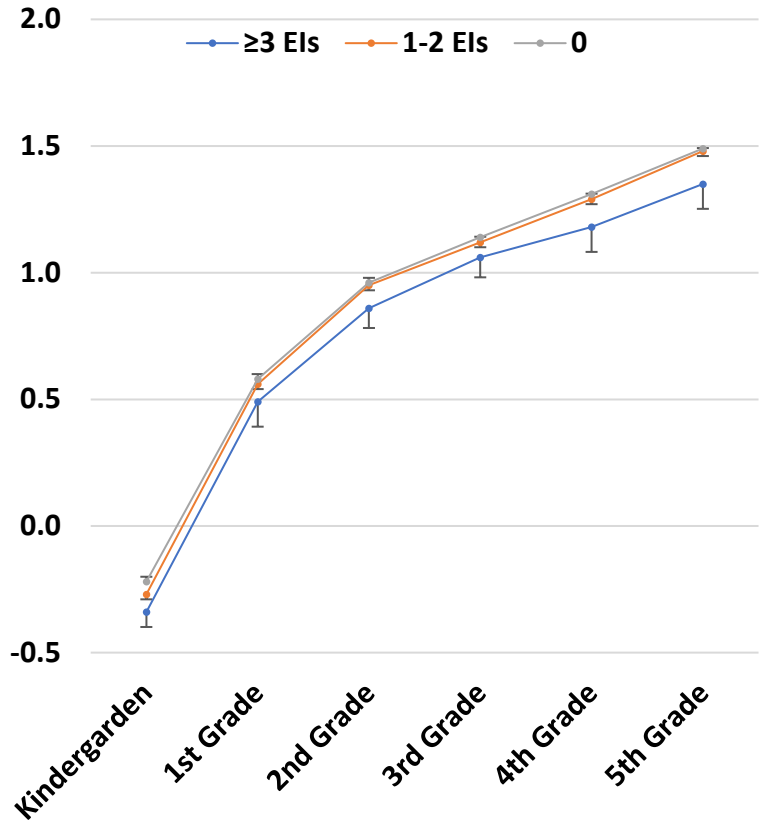


Sensor Locations in Phantom Interior

Chen et al., 2018, and others

Ear Infections





- Ear infections are common
- Incidence declines after kindergarten
- Ear infections and hearing trouble travel together

- Reading
  - Starts around 3 ear infections
  - Impact limited to current year

After Li et al., 2022 APHA presentation; Early Childhood Longitudinal Study (N = 5,492 to 13,400)

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Ototoxic chemicals

- Medications
  - Monitoring
- Organic solvents
  - Styrene
  - Toluene
  - Xylene
  - Ethylbenzene
  - Benzene (?)
- Metals
  - Lead
  - Mercury
- Asphyxiants (potentiation)
  - Carbon monoxide
  - Hydrogen cyanide
- Pesticides
  - Organophosphates
- Smoke
  - Combustion products
    - Solvents
    - Asphyxiants

Morata, et al. (2022)

Inflammation

- Developing understanding
- Biomarkers
  - Cytokines
    - Interleukin-6
    - Interleukin-8
    - (many others)
  - Amyloid plaques
    - Proteins
    - Accumulate
    - Might promote oxidative stress
- NSAIDs
  - Indicates disorder and treatment

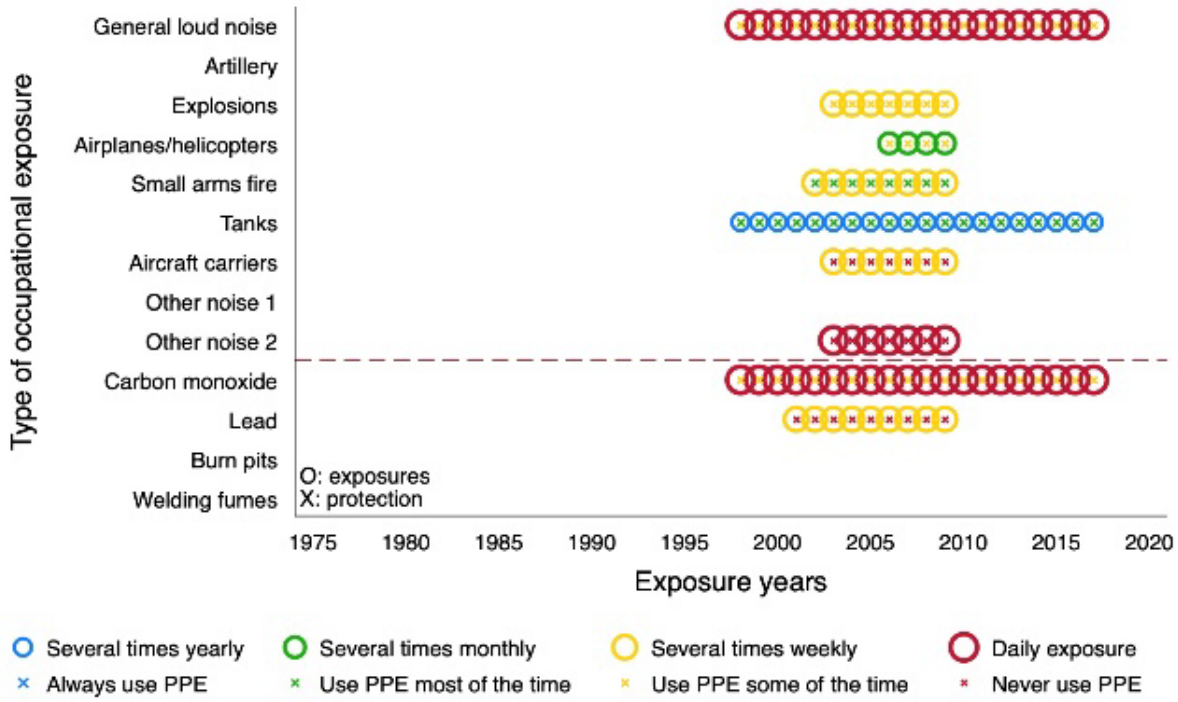
- Related conditions
  - Tinnitus
    - Separate from hearing sensitivity
  - Autoimmune
    - Rheumatoid arthritis
    - Vasculitis
    - Lupus
  - Chronic inflammatory
    - Amyloidosis
    - Polymyalgia
    - Crohn’s
  - Autoinflammatory
    - Atherosclerosis
    - Type 2 diabetes

After Deiters et al. (2023) unpublished analyses

Multidimensionality

- Multiple hazards, even if you only measure noise
  - Sequential vs simultaneous
    - Carbon monoxide half-life: 4-5 hours (room air)

	None/low chemical Row %	Moderate chemical Row %	High Chemical Row %	N
No noise	94	3	3	11,516
Low noise	72	20	8	2,295
Moderate noise	59	22	19	1,649
High noise	57	20	23	3,468
Very high noise	46	27	26	296
Total	81	10	9	19,224



Scalo, et al. (2022) Society for Epidemiologic Research presentation/NCRAR NOISE study

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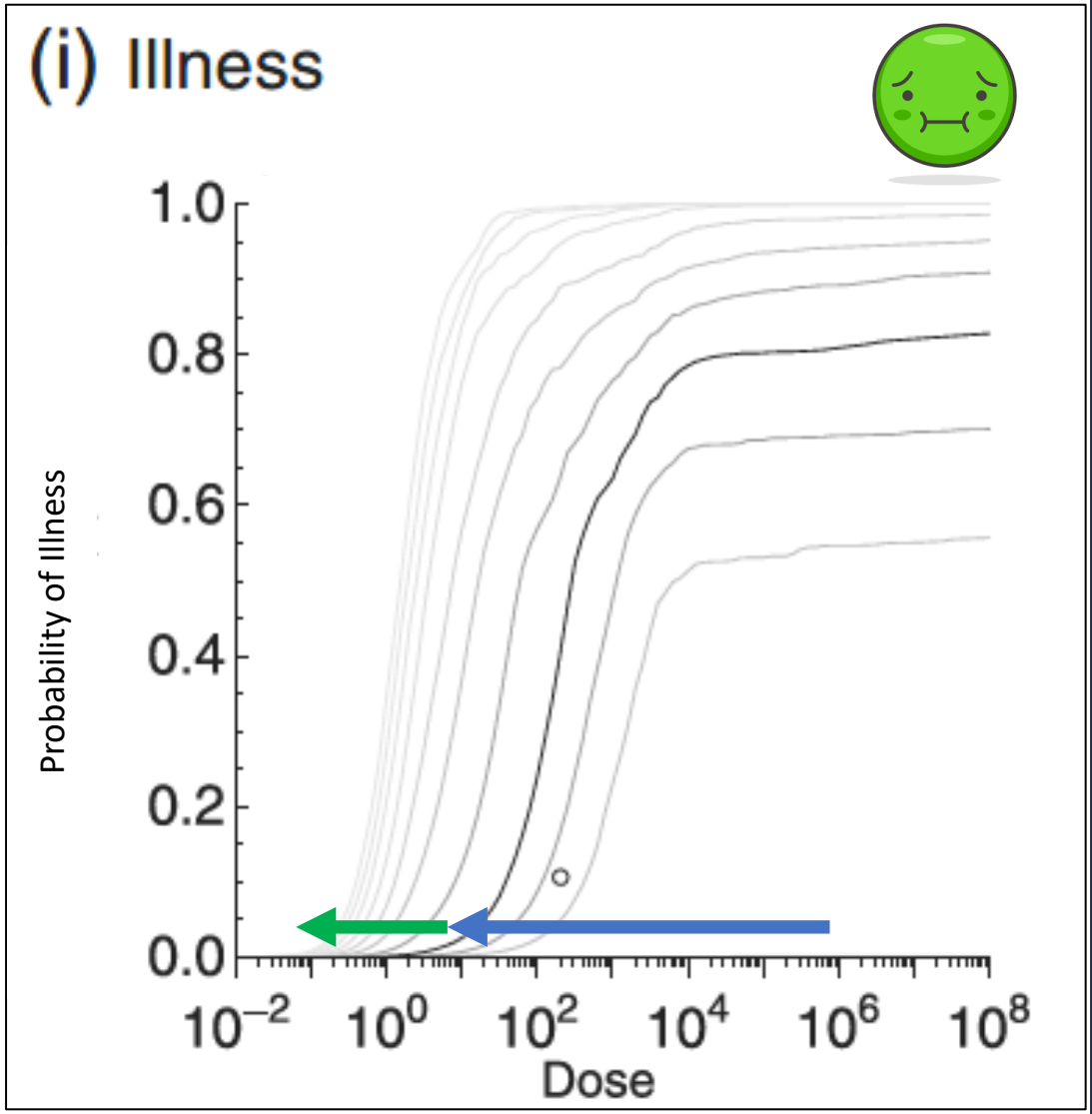
Risk

- Chicken (again!)
- Dose-response relationship
  - Dose: Colony-Forming Units (CFU)
  - Response: Probability of illness
  - Darker curve: Median
- Acceptable risk: Policy
  - Salmonella - USDA
    - Raw max: 1000 CFU/100 g
    - Ready to eat: < 1 CFU/100 g
    - 5-log (10,000x) cooking/processing effect
    - 2-log (100x) safety margin
    - Dose reduced by a factor of 10 million
    - Residual risk: vanishingly small



Teunis, et al., 2010; USDA Salmonella Compliance Guidelines (2017); Canadian Food Inspection Agency (2022)

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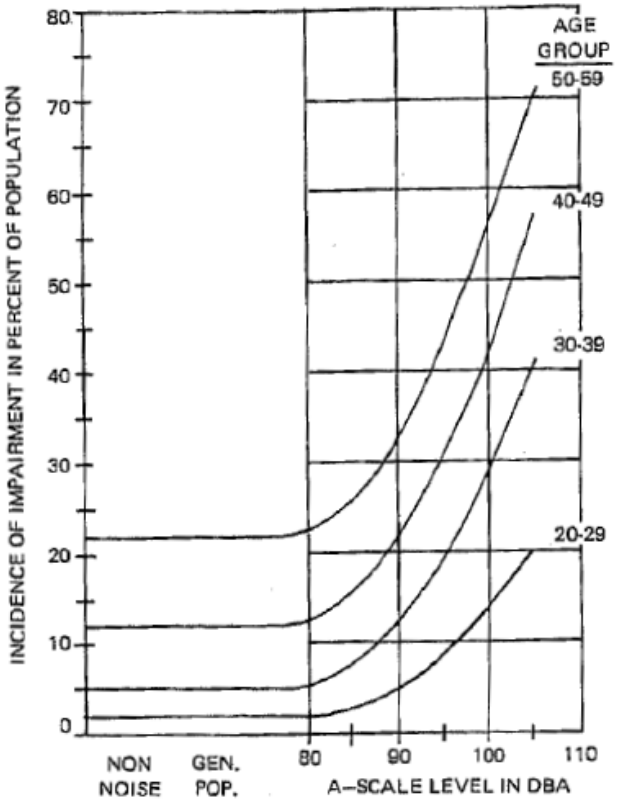
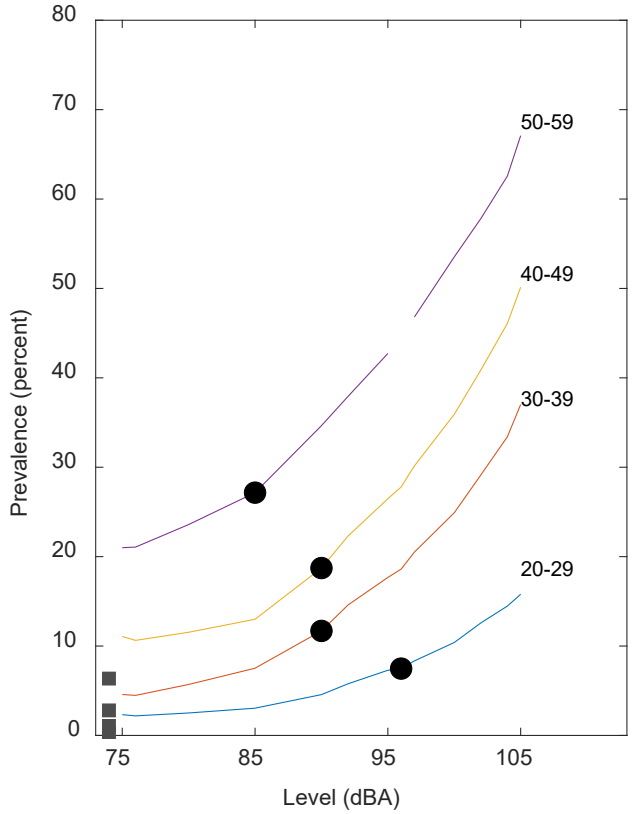
Noise: Continuous (Steady-State)

- Probability of harm as a function of exposure
- "Acceptable" risk is driven by policy
  - 95% certain that 95% will be protected
  - No more than a specified impairment beyond unexposed

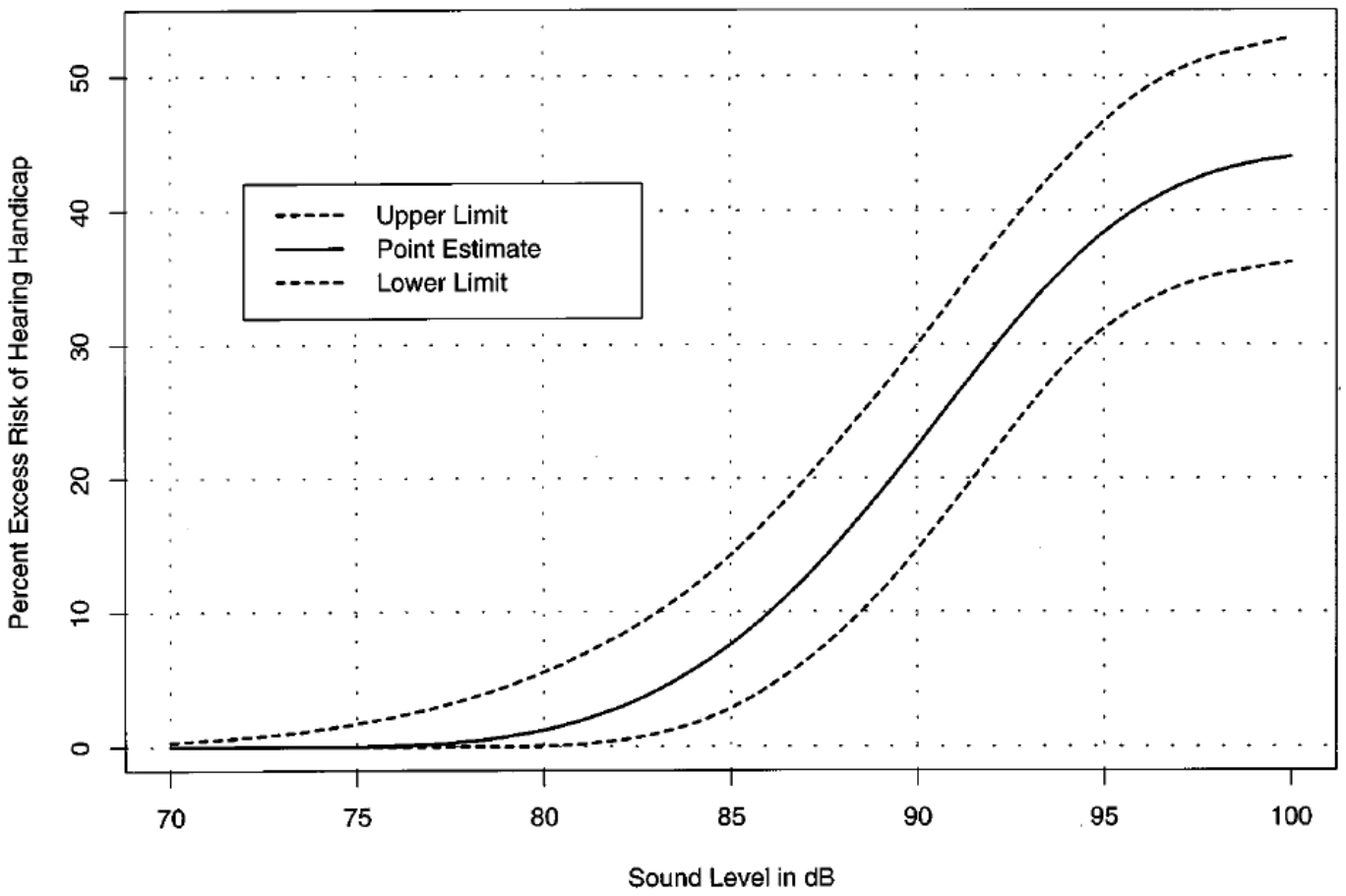




Intersociety Committee (1970) data, [0.5, 1, 2 kHz], lowess smoothed, 5% excess rate

Risk

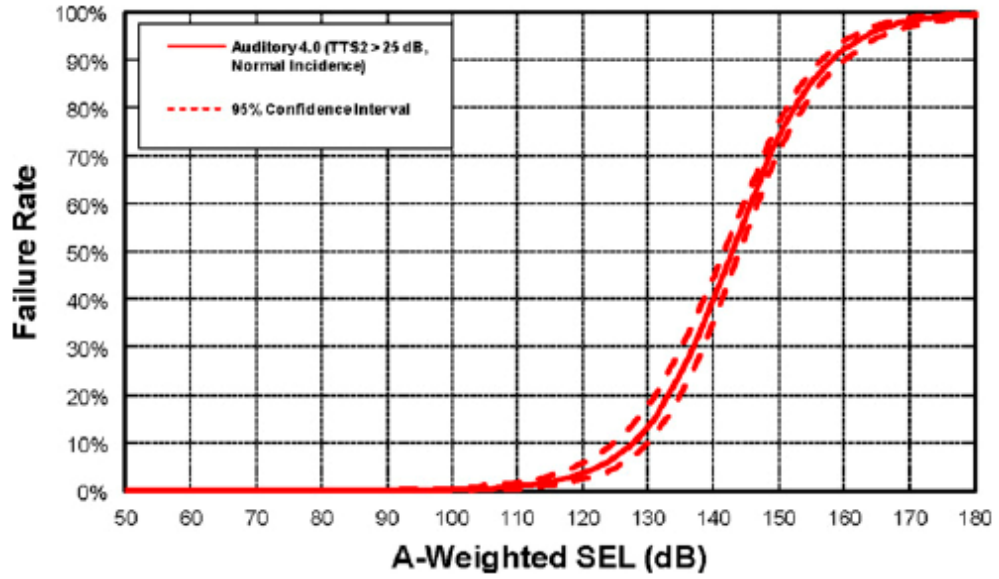
- 8-hour average levels (L_{Aeq8}) 85 and above
  - 8 % excess risk
    - Confidence interval 3 to 15 %

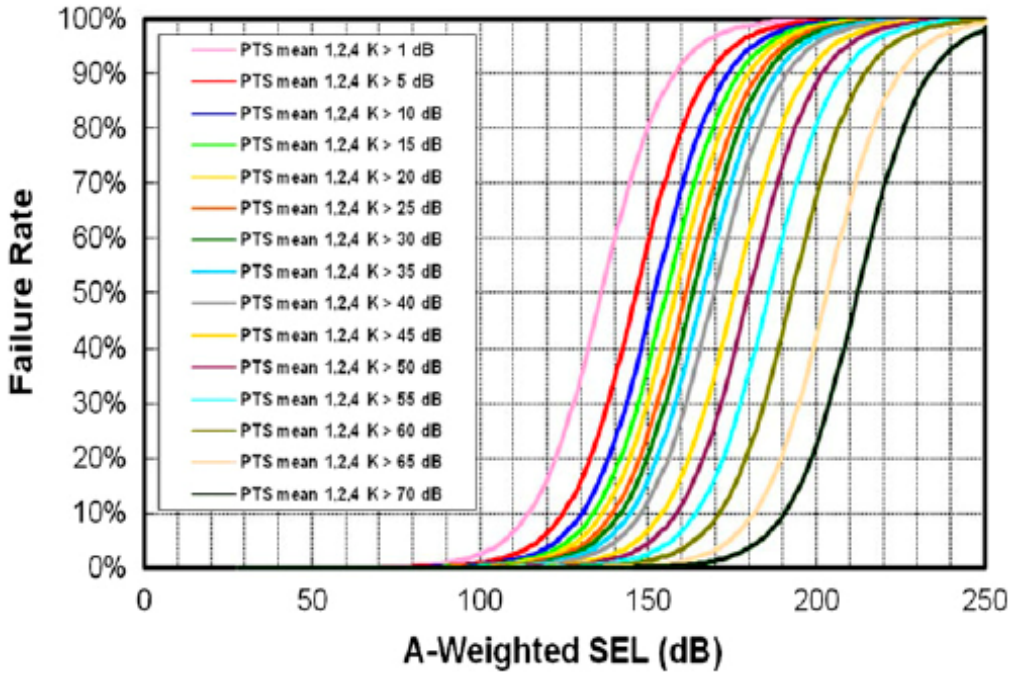


NIOSH (1998)

Risk

- Probability of harm
  - Varies with
    - Harm of interest
    - Exposure metric

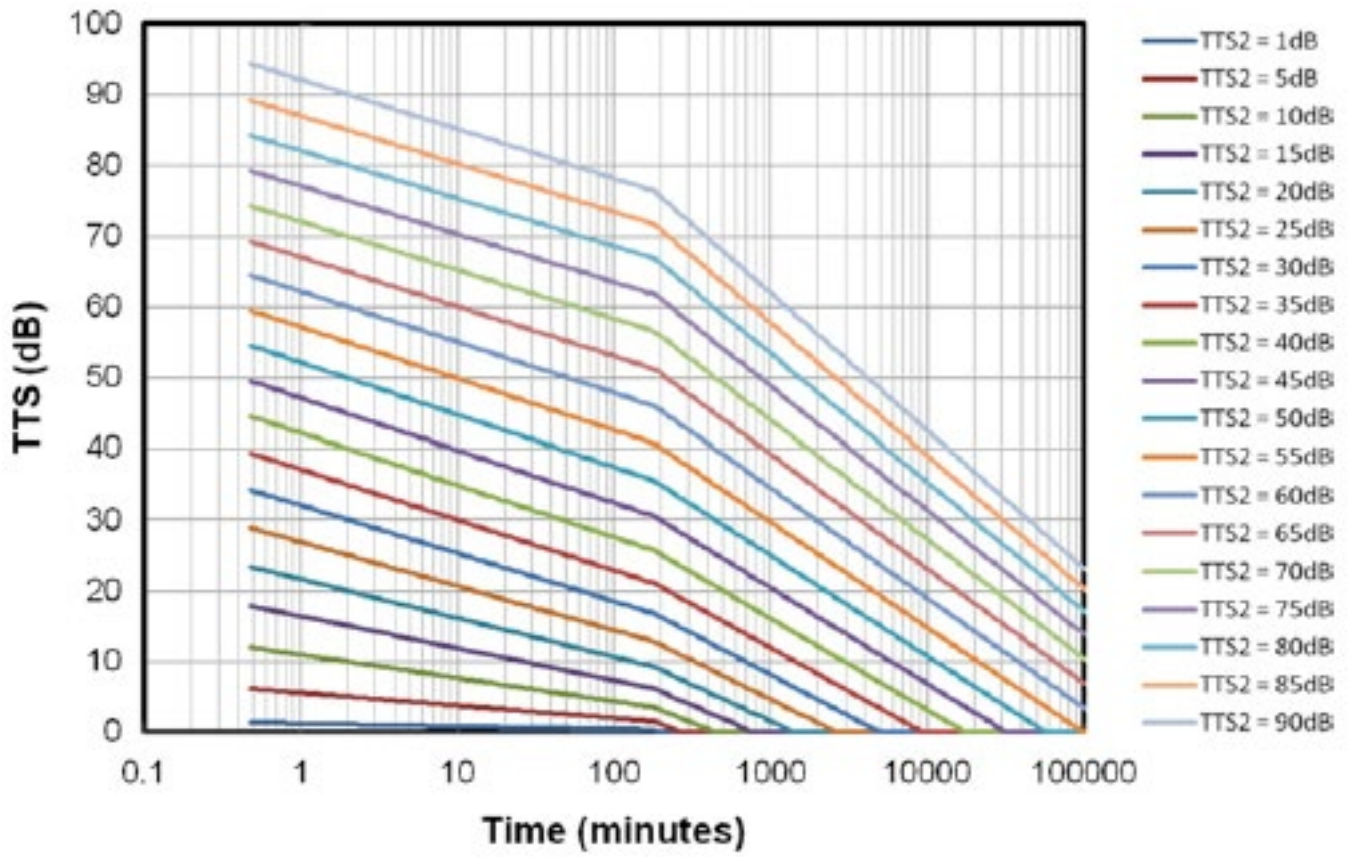




Chan et al., (2016); Note that SEL differs from Leq8 by about 45 dB.

Risk

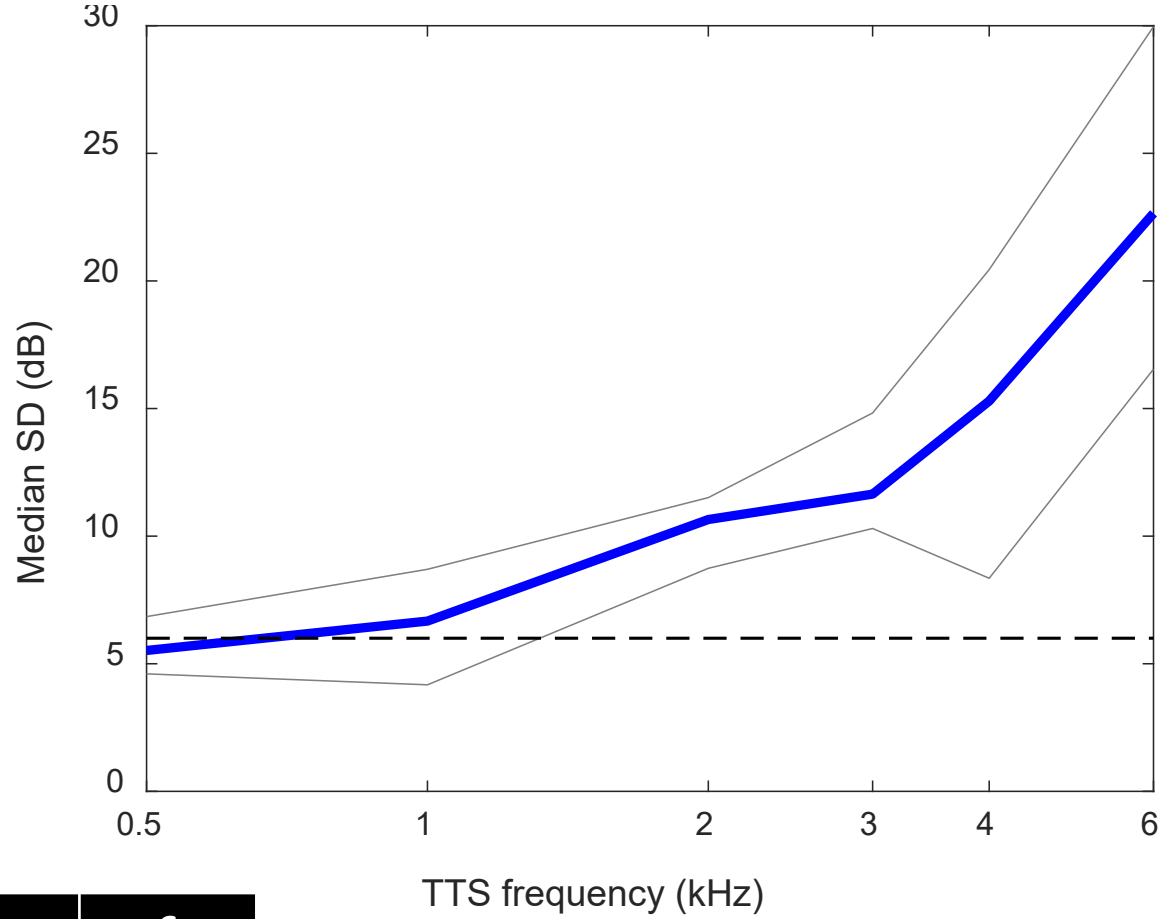
- Risk can be complicated
  - Temporary threshold shift (TTS) can jeopardize other aspects of safety
    - Injury
    - Hazard to others nearby
    - Worker effectiveness and productivity



Chan et al., (2016)

Risk

- Susceptibility: Systematic increase in harm without increased exposure
- Assumption of 6 dB SD is incorrect above 1 kHz.
  - 6 dB at 0.5 kHz
  - 7 dB at 1 kHz
  - 11 dB at 2 kHz
  - 12 dB at 3 kHz
  - 15 dB at 4 kHz
  - 23 dB at 6 kHz
- Combined sample size

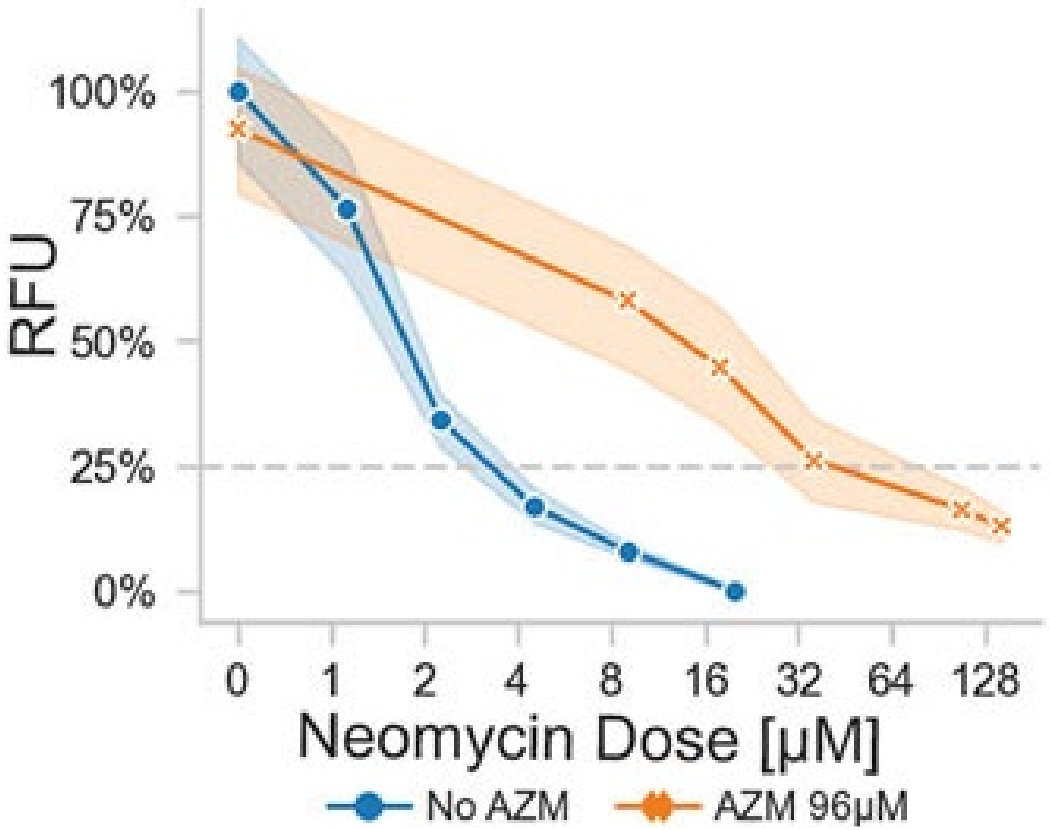


kHz	0.5	1	2	3	4	6
Ears	62	272	321	272	321	272
Studies	10	16	19	16	19	16

Flamme et al. (2020) Acoust. Soc. Am. meeting

Risk

- Dose-response curves are often not available
- Non-human models are common
  - Rodents
  - Cats
  - Amphibians
  - Birds
  - Fish
  - In vitro
- Surrogate outcomes are useful but insufficient
  - Histology
  - Electrophysiology
  - Uncontrolled observations



Bustad et al., 2024 (Azithromycin as mediator in Zebrafish model)

SASRAC

Mitigation

- Eliminate hazard
  - Engineering and Administrative controls (possibly)
- If nothing else, reduce risk
  - Some hazard remains
  - Hearing Protection Devices
  - Some engineering and administrative controls

- Field-compatible technology
  - High-attenuation earphones
  - Wireless/tablet interface
- Objective: Austere military environment
  - Every other place is easier

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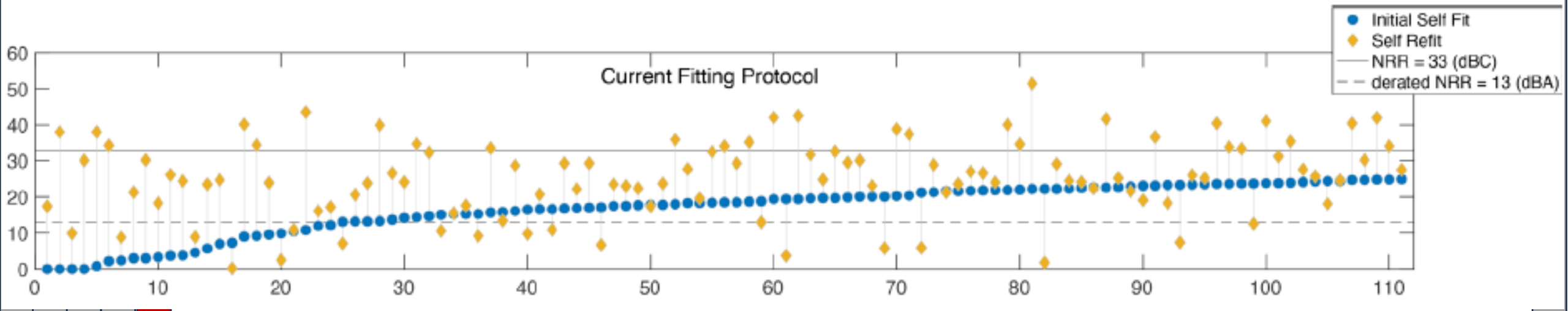
Personal Attenuation Ratings (PAR)

- Lab measures indicate capacity, not effectiveness
  - CSA Z94.2-14 (2019) based on experimenter fit, N = 10, 3 insertions (Octave bands and NRR)
  - Individual testing preferred



Murphy, et al. (2022)

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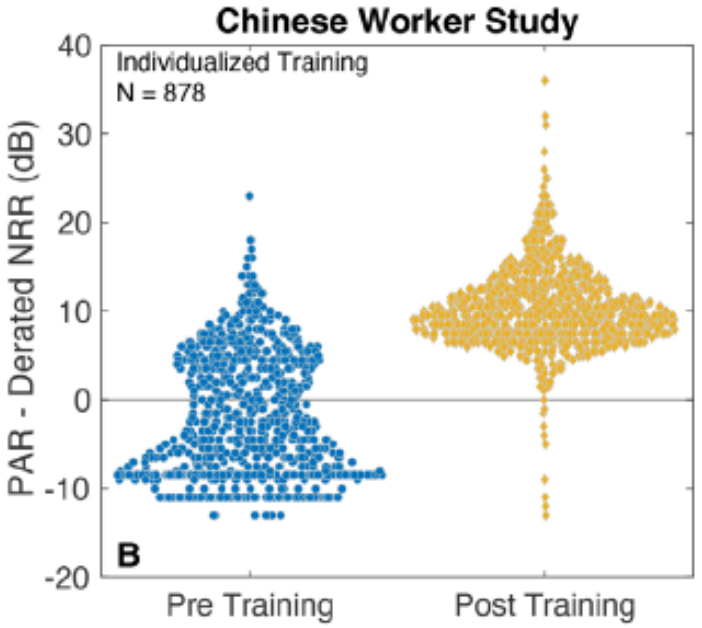
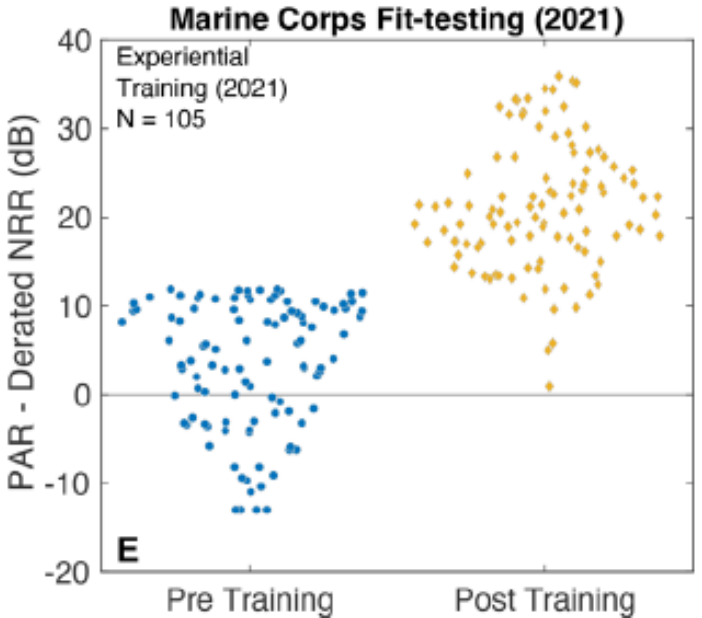
Personal Attenuation Ratings (PAR)

- PAR
  - Documents individual attenuation
  - Can identify people who need training or more compatible HPDs, given exposure
  - Methods
    - Microphone in real ear (MIRE)
    - Real ear attenuation at threshold (REAT)
  - Possible integration with exposure records and routine audiometry
  - Some generic, some manufacturer-specific
  - Earplug PAR is both easier and more important



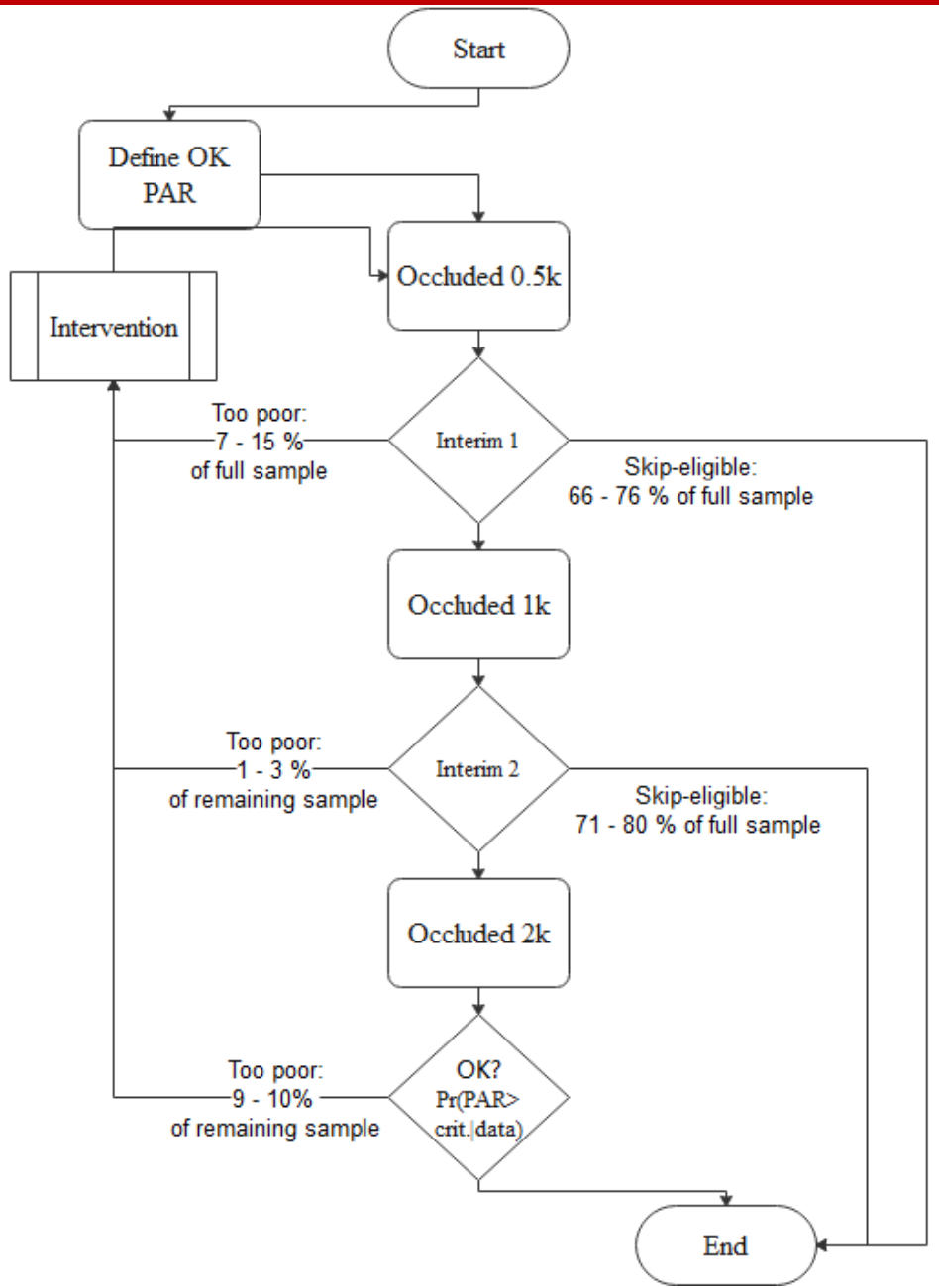


Murphy, et al. (2022)

Personal Attenuation Ratings

Background
Harm
Hazard
Risk
Mitigation

- Incremental assessment of REAT PARs
  - Only 3 frequencies needed
    - 0.5, 1, 2 kHz
    - 1, 2, 4 kHz (passive nonlinear HPDs)
- For each frequency
  - Evidence of sufficiency
  - Evidence of inadequacy
  - Not conclusive, get more info.
- More skips when PAR target is lower

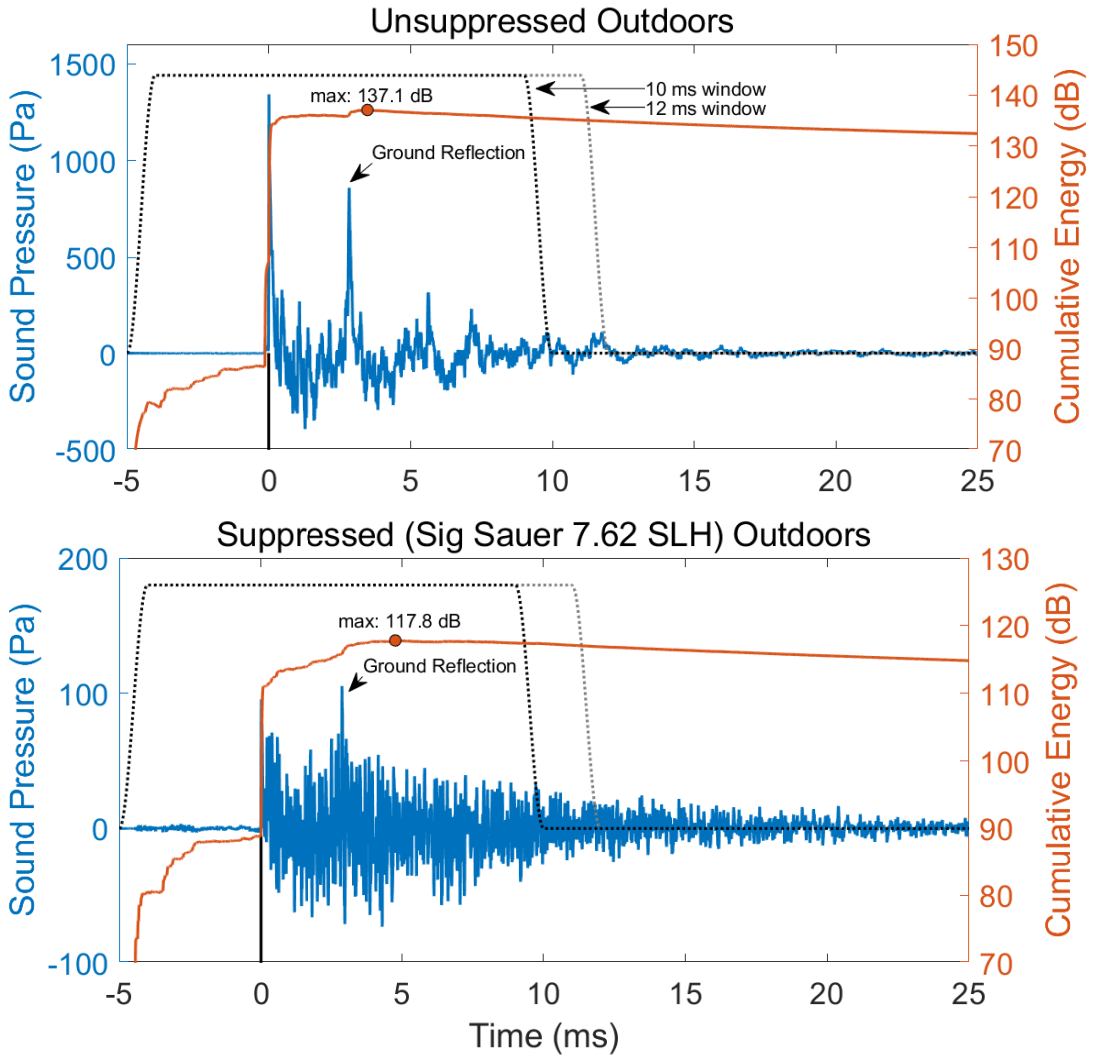


Conclusion

Flamme et al., 2023 IHPFT symposium (Criterion PAR = 18 dB; Test N > 5600);

Mitigation

- Firearm suppressors
  - Engineering control (muffler)
  - Restricted
  - No recognized standard
    - Instrumentation
    - Procedure
    - Analysis
  - Likely to become more important
    - Canadian Modular Assault Rifle (CMAR) program



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Conclusion

Background
Harm
Hazard
Risk
Mitigation
Conclusion

- Framework
  - Harm
  - Hazard
  - Risk
  - Mitigation
- Different hazards → different harms
  - Same harm, multiple causes
- Harms occur at different doses
  - Temporary v. permanent threshold shift
  - Cochlear synaptopathy

- Some hazards travel together
  - Noise and asphyxiants
  - Noise and solvents
    - Propellant combustion products
- Prevention of auditory harm, not just noise-induced harm
- Case history
  - Screen broadly for hazards/risk factors
  - If risk (dose-response) is known, is status consistent with the dose?
    - If not, keep looking
- Biomarkers in future?

After Deiters et al. book chapter in Alessio & Marron (2024)

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Questions?

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