Standardised Hearing Loss Risk Profiles with State-Space Models

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1. Context

Hearing loss affects over **430 million** people globally [1]. It severely impacts quality of life, communication, and leads to increased **health risks** [2].

Despite this, **current prevalence estimates** are often outdated and lack representative data, especially in Europe [3].

Our work aims to fill these gaps by establishing a **population-level benchmark for hearing loss risk profiles**, utilizing both audiogram and speech-in-noise tests to enhance precision in clinical diagnostics and public health strategies.

2. Contributions

Novel state-space model (SSM) inspired by approaches like Lee-Carter, adapted to analyze hearing loss patterns. The contributions are threefold:

- **Innovative model formulation for benchmarking risk profiles.**
- **Definition of demographic-specific hearing loss incidence.**
- **Integration of relationships between audiogram and speech tests to assess both sensitivity and clarity in hearing.**

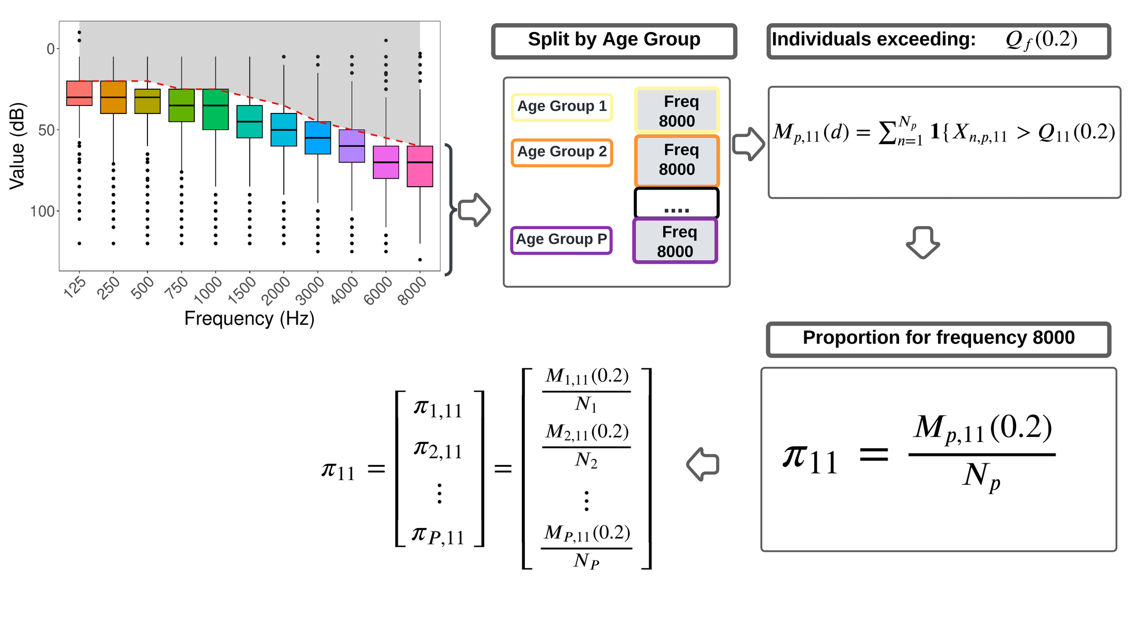
3. Hearing Loss Proportion

We define the **empirical quantile** $Q_f(d)$ for frequency f of the audiogram using the empirical cumulative distribution function (ECDF) of the data comprising the total number of N patients as

$$Q_f(d) = \hat{F}^{-1}_{X_{\cdot,\cdot,f}}(d) \quad \text{with}$$

$$\hat{F}_{X_{\cdot,\cdot,f}}(x) = \frac{1}{N}\sum_{i=1}^{N} \mathbf{1}(X_{\cdot,\cdot,f} \leq x)$$

where $X_{\cdot,\cdot,f}$ represents the thresholds of frequency f.



References: 1. World Health Organization. (2021). *World Report on Hearing*. WHO.
2. Lisan, Q., et al. (2022). Prevalence of hearing loss and hearing aid use among adults in France in the CONSTANCES study. *JAMA Network Open*, 5(6), e2217633.
3. Haeusler, L., de Laval, T., & Millot, C. (2019). *Etude quantitative sur le handicap auditif à partir de l'enquête "Handicap-Santé"*: document de travail, série études et recherches. Retrieved from https://drees.solidarites-sante.gouv.fr/sites/default/files/2020-09/dt131.pdf.

4. Model Formulation

For each of the empirical quantiles $Q_f(d)$ and the audiogram data matrices for each age group $\{\mathbf{X}_{N_p \times F}\}_{p=1}^{P}$, one counts how many patients within each frequency column exceed $Q_f(d)$, for each of the P matrices, giving relative proportions

$$\boldsymbol{\pi}_{p,f} = \frac{1}{N_p} M_{p,f}(d) = \frac{1}{N_p}\sum_{n=1}^{N_p} \mathbf{1}\{X_{n,p,f} > Q_f(d)\}$$

We seek a dynamic structural explanation of the age term structure proportions, $\tilde{\boldsymbol{\pi}}_f$ of relative hearing loss performance per frequency under the SSM dynamics given by

$\mathcal{M}_{\mathrm{B},d}$:**Baseline Model.**

$$\tilde{\boldsymbol{\pi}}_f = \boldsymbol{\alpha}^{(B)} + \boldsymbol{\beta}^{(B)}\kappa_f^{(B)} + \boldsymbol{\epsilon}_f^{(B)},$$
$$\kappa_f^{(B)} = \theta^{(B)} + \phi_1^{(B)}\kappa_{f-1}^{(B)} + \omega_f^{(B)}$$

$\mathcal{M}_{\mathrm{E},d}$:**Extended Model.**

$$\tilde{\boldsymbol{\pi}}_f = \boldsymbol{\alpha}^{(E)} + \boldsymbol{\beta}^{(E)}\kappa_f^{(E)} + \gamma_{(Q)}^{\intercal}\,\boldsymbol{\pi}^{(Q)} + \gamma_{(N)}^{\intercal}\,\boldsymbol{\pi}^{(N)} + \boldsymbol{\epsilon}_f^{(E)},$$
$$\kappa_f^{(E)} = \theta^{(E)} + \phi_1^{(E)}\kappa_{f-1}^{(E)} + \omega_f^{(E)}$$

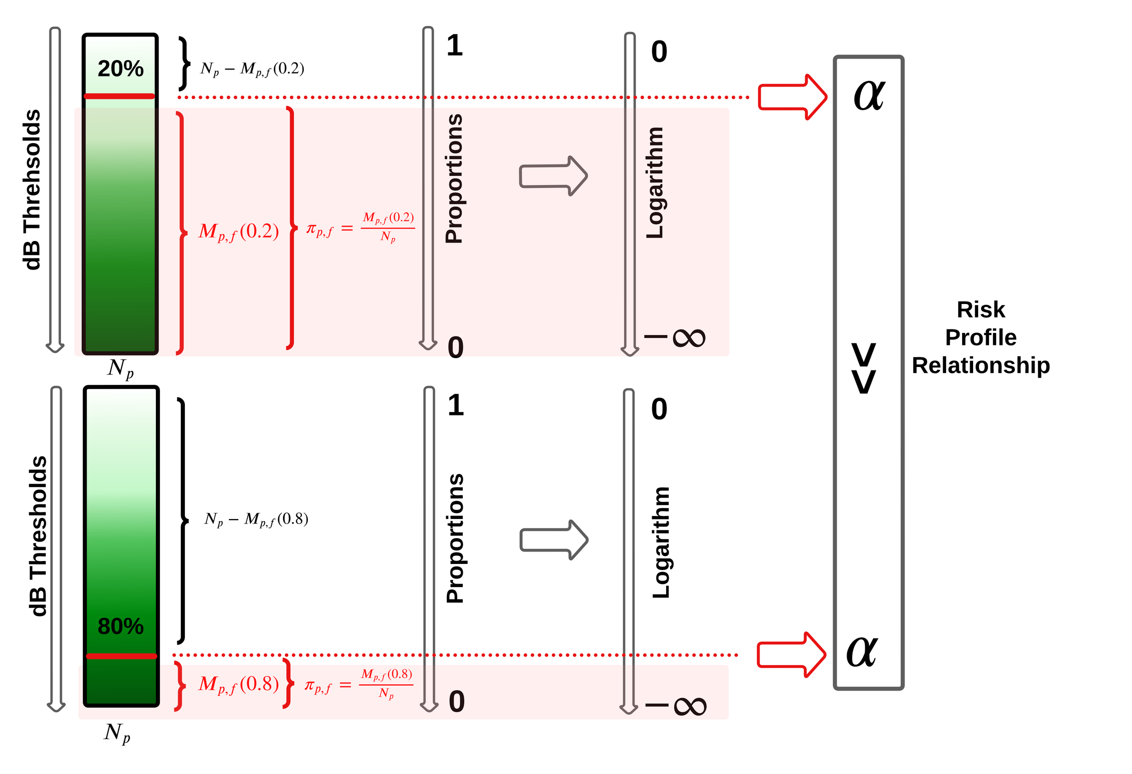
We run this model by considering the **overall** population and segments of population, i.e. by **hearing loss degree** and **sex**.

5. Model Interpretation

$\boldsymbol{\alpha} = (\alpha_1, \dots \alpha_P)^{\intercal}$ **Age-specific intercepts** measuring **baseline hearing loss level** for each age group.

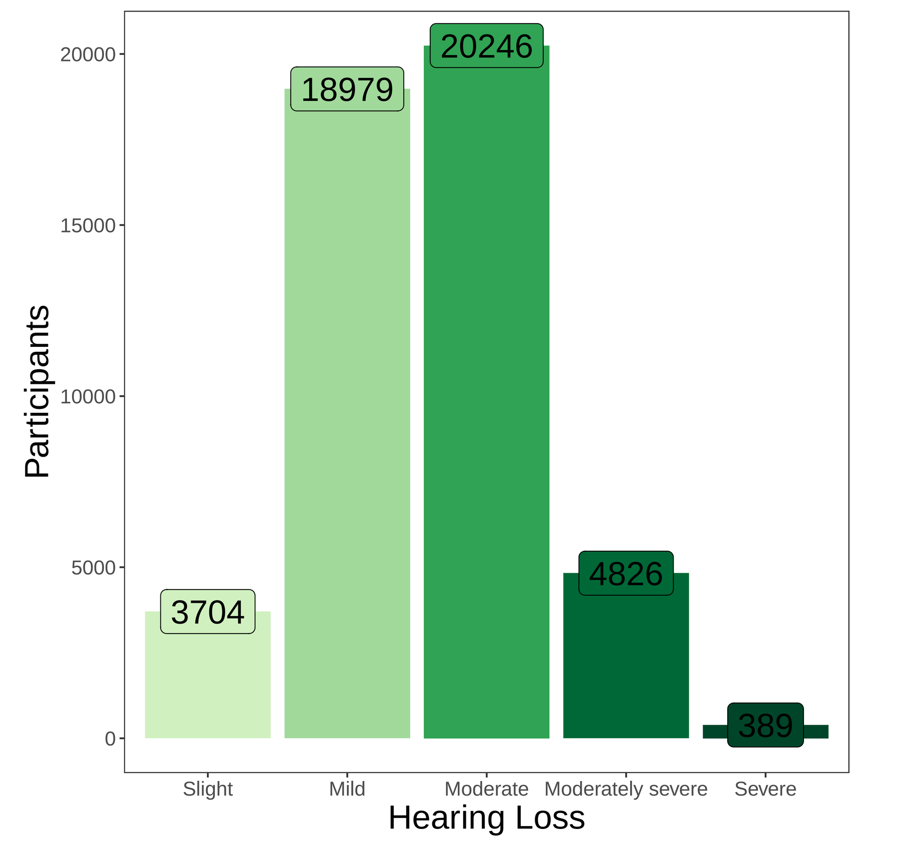
κ_f Common **baseline trend in hearing loss proportions** across all age groups for frequency f.

$\boldsymbol{\beta} = (\beta_1, \dots \beta_P)^{\intercal}$ **Age-specific sensitivity** of hearing loss proportions $\tilde{\boldsymbol{\pi}}_f$ to a change in the general trend of hearing loss κ_f.

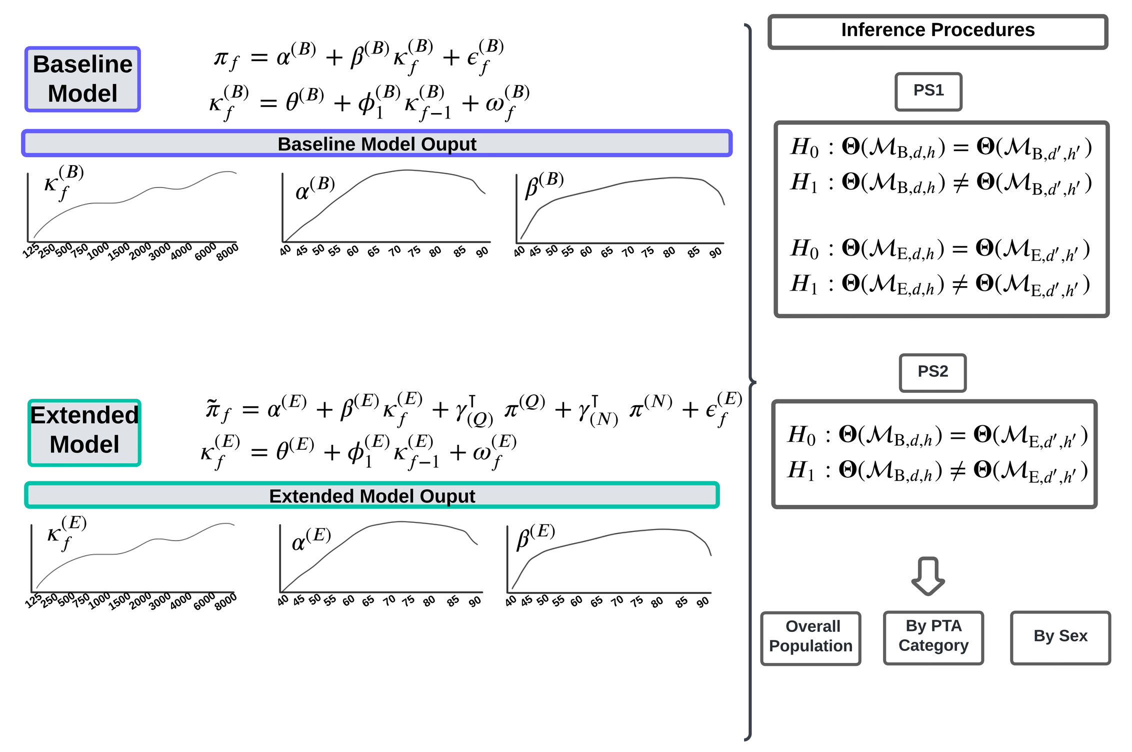


6. Dataset

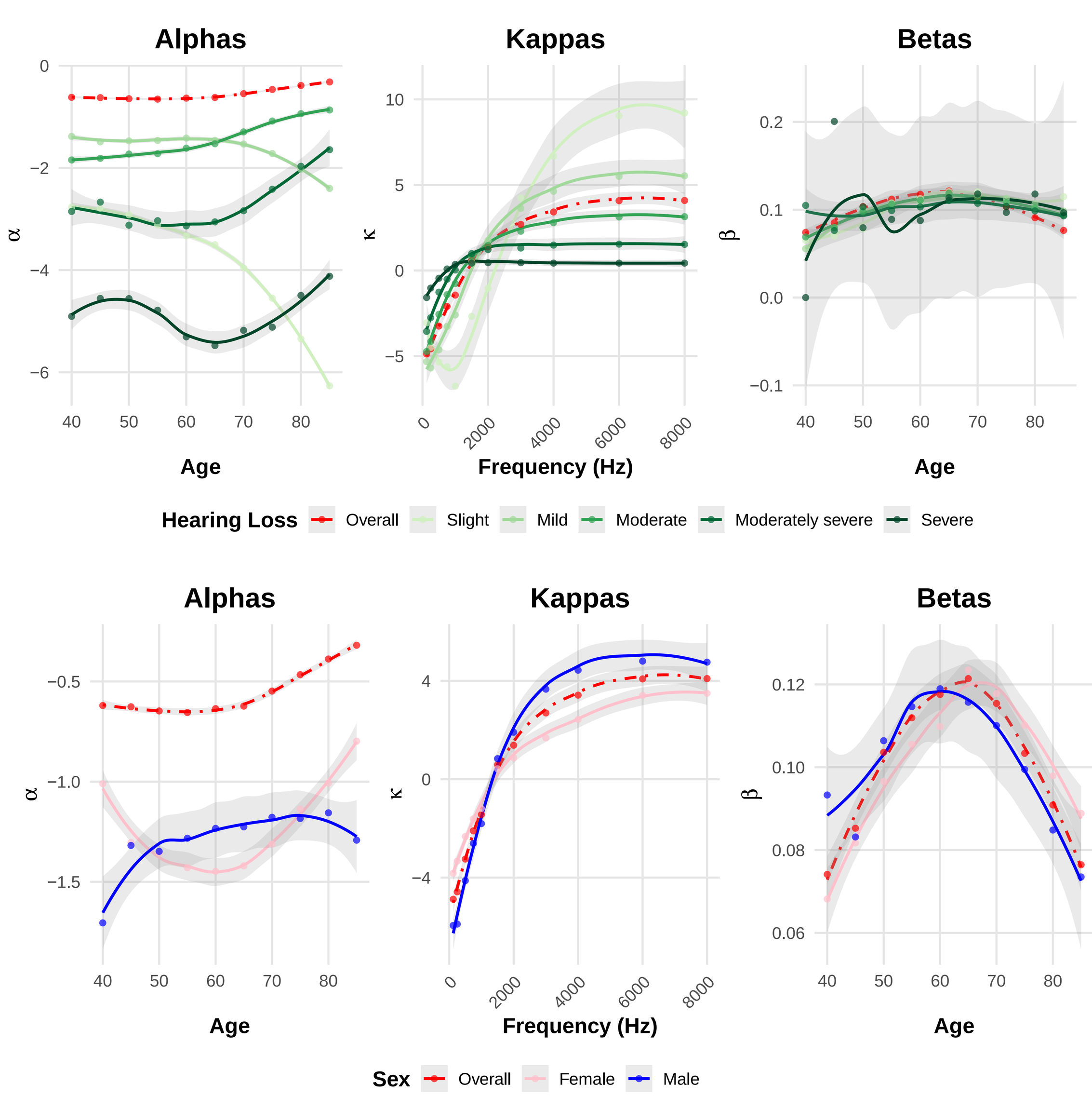
Participants completed three measurements being **audiogram**, **speech-in-quiet** and **speech-in-noise**.



7. Statistical Inference



8. Risk Profiles



9. Conclusions

- Developed a **methodology** for **standardized risk profiles** using audiogram and speech tests.
- **Risk Insights**: **Age** and **frequency** are critical; risk rises after age 65. **Hearing loss differences**: SPIN crucial for slight to moderate loss; SPIQ for severe cases.
- **Personalized Interventions**: Supports tailored assessments by age, severity, and gender.

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