Converging fNIRS, EEG, and behavioral measures highlight DNN noise-reduction advantages during speech-in-noise perception and natural conversation

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Seven wonders of the modern *hearing aid* world?

1) Directional microphones (early 1970's)
2) Wide dynamic range amplitude compression (late 1980s)
3) Digital signal processing (early 1990s)
4) Advanced feedback management (early 2000s)
5) Real-time environmental classification (early to mid 2000s)
6) Rechargeable hearing aids (about 10 years ago)
    - History buffs, do you recall the Siretta 339 of 1966?



Seventh wonder of the modern HA world?

7) Integration of modern AI methods in HA processing

- Leveraging AI in hearing aid function can introduce new possibilities and potentially solve longstanding problems
- Use cases for AI in hearing aids:
  - Advanced real-time environmental classification
  - Solutions for externalization and spatialization
  - Multi-sensor integration
  - Predicting wearer intent and state
  - Advanced noise reduction
- Aspects of AI (i.e., machine learning, neural networks) have been in use in HA DSP ~25 years (e.g., environmental classification)



"It's a special hearing aid. It filters out criticism and amplifies compliments."

SNHL & Signal-to-Noise Ratio (SNR) Deficits…

- ~ 6 dB reduction in effective SNR
  - Plomp & Mimpen (1978; 1979)
  - QuickSIN normal to mild loss is ~ 3 to 7 dB
  - QuickSIN normal to moderate loss is ~ 7 to 12 dB
- Poor SNR relatively rare in daily listening (~10%)
  - Wu et al. (2018) 894 real-world situations
    - 63% SNRs between +2 and +14 dB
    - 7.5% SNRs below 0 dB
- Number one complaint in nearly every survey
    - Rare but frustrating events leave their mark
    - Low positive SNRs are frustrating too



SNHL & Signal-to-Noise Ratio (SNR) Deficits…

- ***Traditional noise reduction*** (TNR)
  - Spectral subtraction, Weiner filtering, modulation-based methods
  - Reduces listening effort and annoyance associated with noise but provides minimal SNR benefit
- ***Conventional directional microphone*** strategies
  - Provide +2 to 5 dB SNR benefit on standard tests Substantially less improvement in real-world
- ***DNN Noise Reduction*** (DNN_{NR})
  - Leverage the computational power of AI and potentially alleviate some of the burden from directional systems
- ***Challenges***: Variation in methods used to quantify deficits and to measure benefits
  - Stimuli, environments, behavioral tasks, objective measures, device parameters



Research Questions

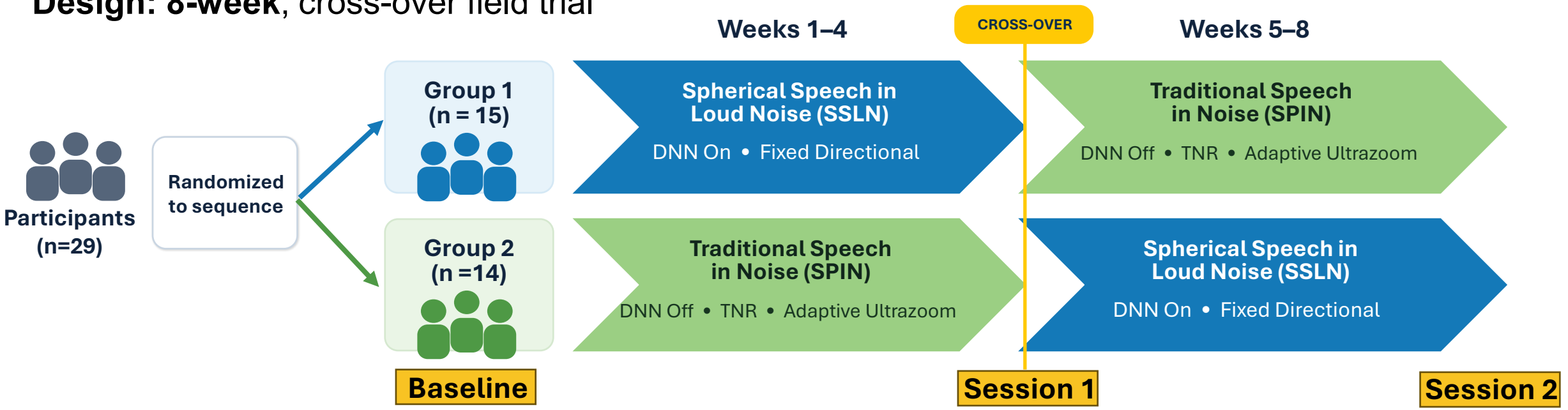
1. Does DNN_{NR} improve speech-in-noise performance relative to TNR methods?
2. Does DNN_{NR} facilitate improved cognitive function in linguistically demanding speech-in-noise tasks? (e.g., Helfer & Jesse, 2015)
3. Can we identify specific neural markers with EEG or fNIRS or both that support behavioral changes? (e.g., Karawani, et al., 2022; Vaisberg et al., 2025; Wilfroff et al., 2025)
4. Do experienced users prefer DNN_{NR} or TNR while actively participating in multi-person conversations?
5. Can extended use of DNN_{NR} over time induce behavioral change or neural plasticity?

Methods

Participants

- 29 older (age 75.3 ± 8.3 yrs; 13 female, 15 male, 1 other) experienced hearing aid users (5.5 ± 4.6 yrs) with moderate to severe SNHL (PTA: left 41.9 ± 8.0, right 42.9 ± 7.1 dB HL)
- Newly fitted with Phonak Audeo Sphere Infinio BTE hearing aids with closed domes

Design: 8-week, cross-over field trial



Live Evaluation of Auditory Preference (LEAP)



Task: (Smeds et al., 2021)

- Two, 3-minute triadic conversations
  - Topics randomly chosen from a fixed set
  - Agree on a list of things to prepare for a hurricane for someone who has never experienced one before
- Participant toggles between SSLN and SPIN programs using tablet PC during the conversation
- Preference via paired comparison (4 options):
  - Program 1
  - Program 2
  - No Preference
  - No Difference
    - Can't hear a difference between programs

Live Evaluation of Auditory Preference (LEAP)



Speech Stimuli:

- Live three-person conversation
  - Participant, two confederates

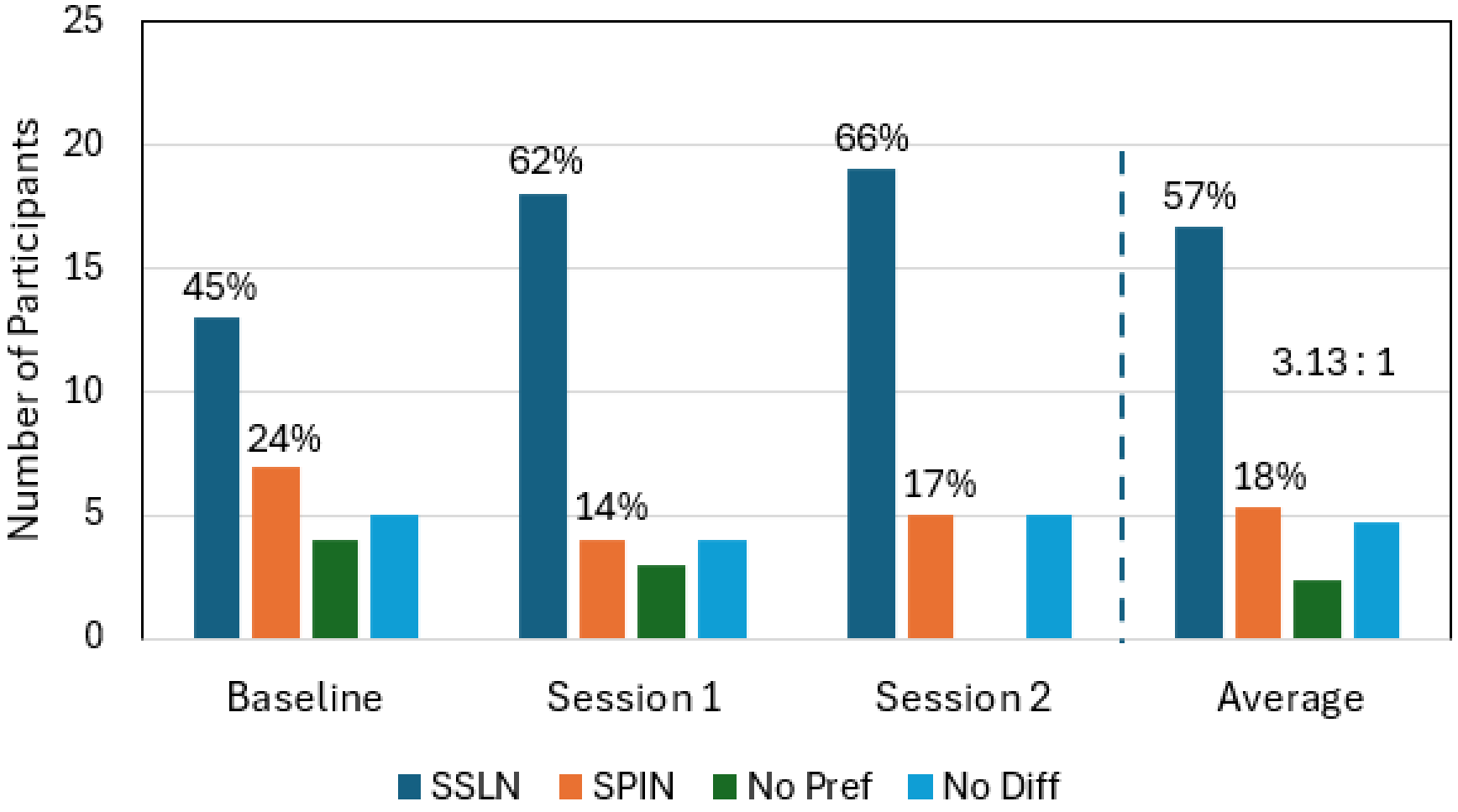
Interferer:

- Continuous, diffuse café (ARTE #2) + LTSSN
- Diffuse background in moderate reverberation
  - 8 loudspeakers
- 73 dBC overall level

Hearing Aid Conditions:

- SSLN (DNN_{NR} On, Fixed Directional)
- SPIN (DNN_{NR} Off, TNR, Adaptive Ultrazoom)

Live Evaluation of Auditory Preference (LEAP)



- Rarely have no preference
- Sometimes cannot hear a difference
- 3.13 to 1 Preference for SSLN over SPIN

Speech Stream Segregation Task (SSST)

Speech Sentences: TVM sentence corpus (Helfer & Jesse, 2015)

"Theo/Victor/Michael discussed the *Target1* and *Target2* today"

4-alternative forced-choice response for each Target, touchscreen response interface

- *Cognitive Load* modulated by target word lexical frequency (Frequent, Rare)

  "Victor discussed the wave and the time today" – Frequent

  "Michael discussed the hook and the lush today" – Rare

- Target talker location randomized on each trial: -90, -45, 0, 45, 90 degrees

Interferer: Continuous, diffuse party noise (ARTE #2) + LTSSN

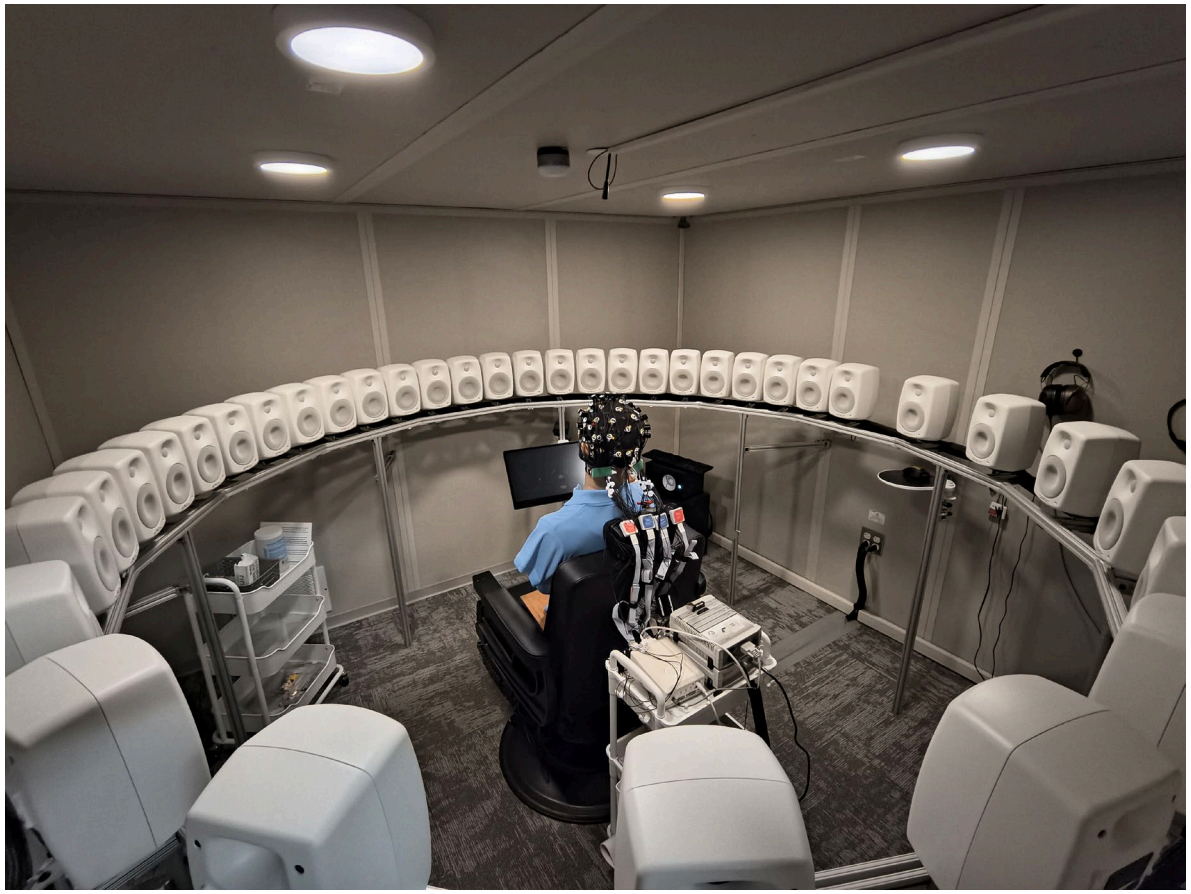
- 73 dBC overall level

SNR: Individualized at either -3, -5, -6 dB following an initial adaptive run

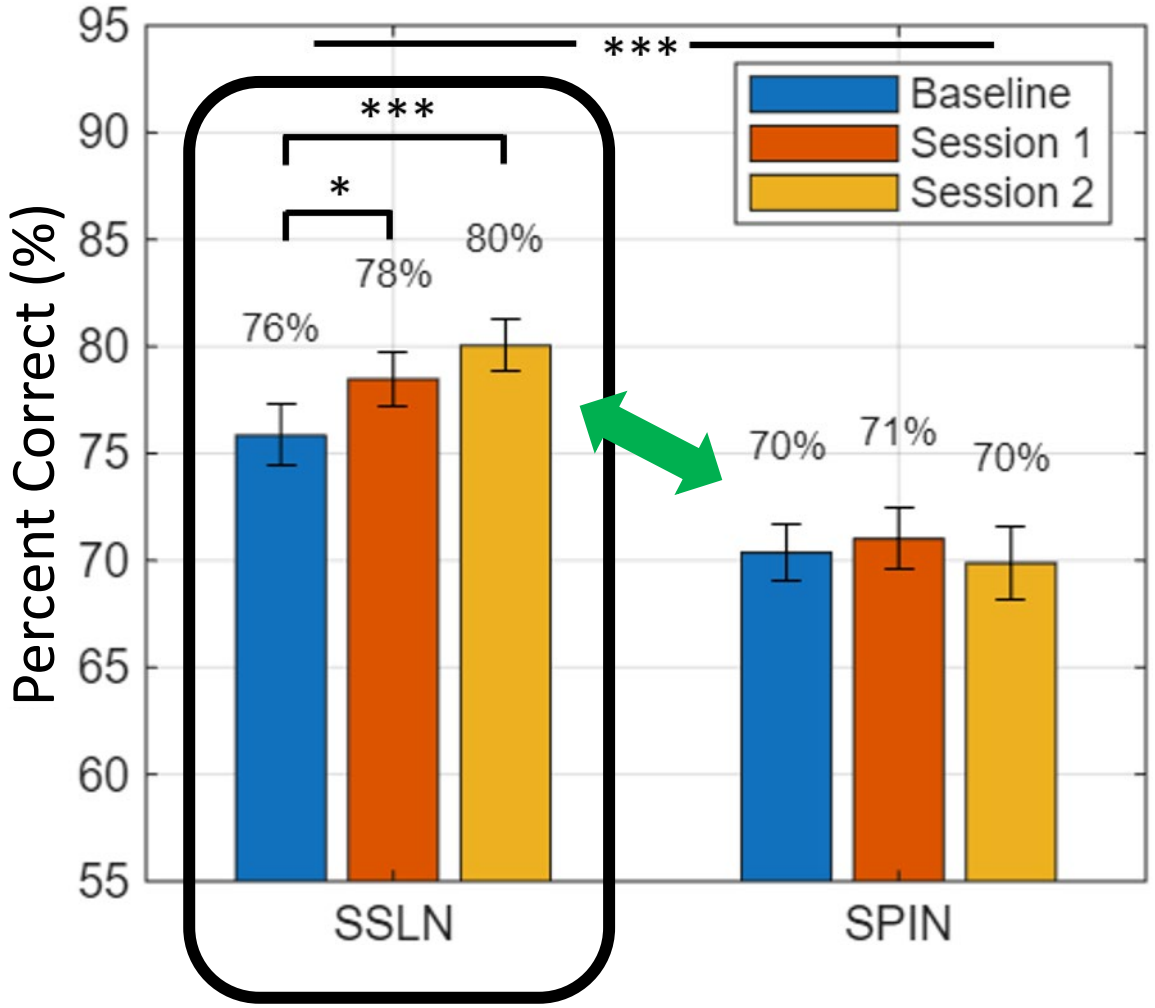
SSST Outcome Measures

Concurrent Measures:

- Behavioral – Performance in percent correct
- Behavioral – Response latency in seconds
- Neural – fNIRS (NIRX)
  functional Near-Infrared Spectroscopy
  - 12 optode pairs, 31 channels + 8 short channels
- Neural – EEG 32-channels (Brain Vision)
- Cognitive – Word frequency, neural activity

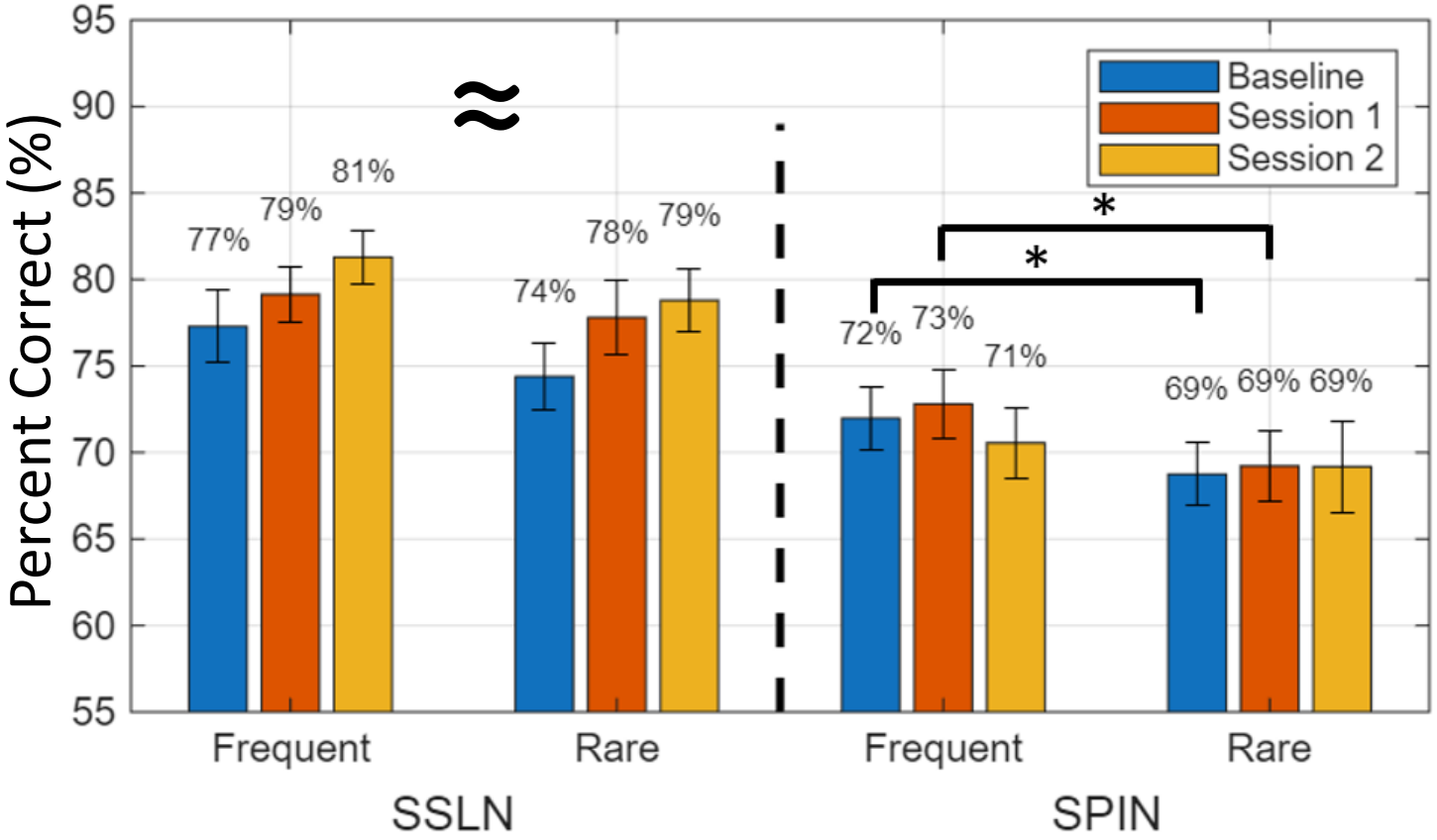


SSST: DNN_{NR} Improves Performance Accuracy



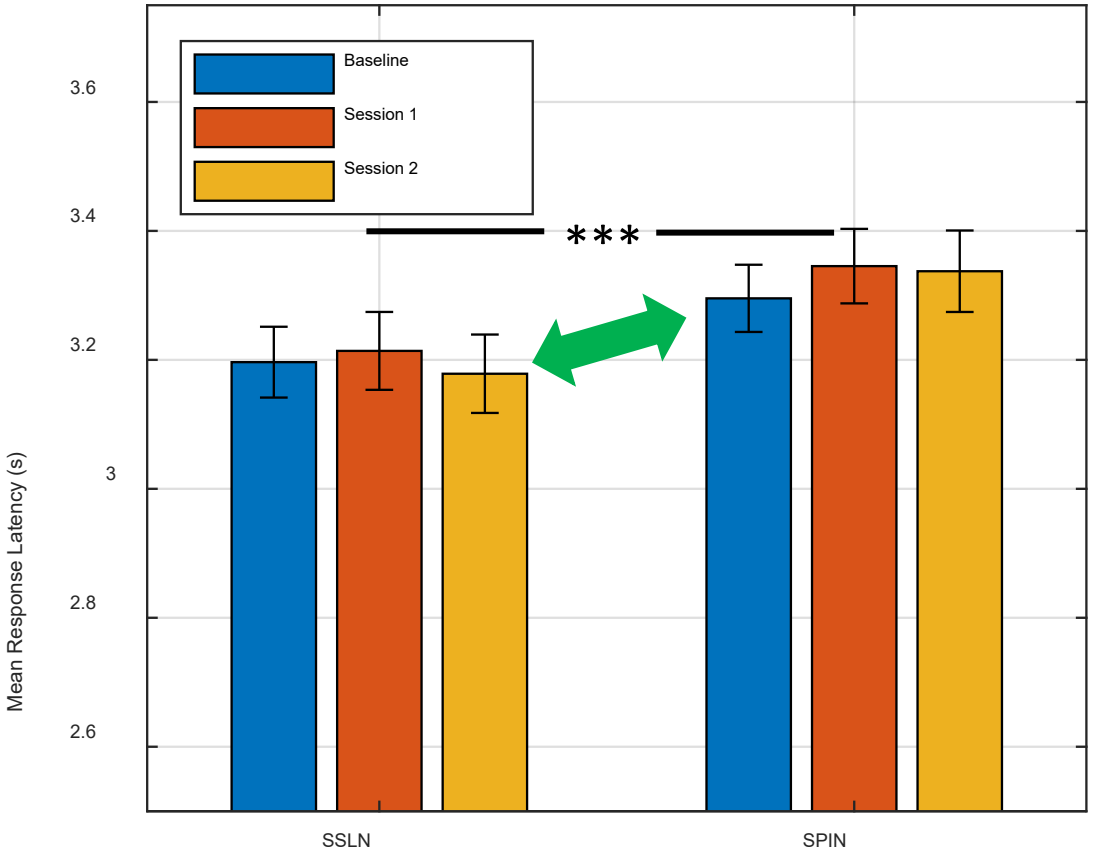
- DNN_{NR} Effect
  - 6 – 10% improvement in SSLN over SPIN ($p < 0.001$)
- Longitudinal Effect
  - Significant improvement
    - Baseline to Session 1 ($p = 0.048$)
    - Baseline to Session 2 ($p < 0.001$)
- HA Crossover Effect
  - No Group difference

SSST: DNN_{NR} Impacts Cognitive Function?



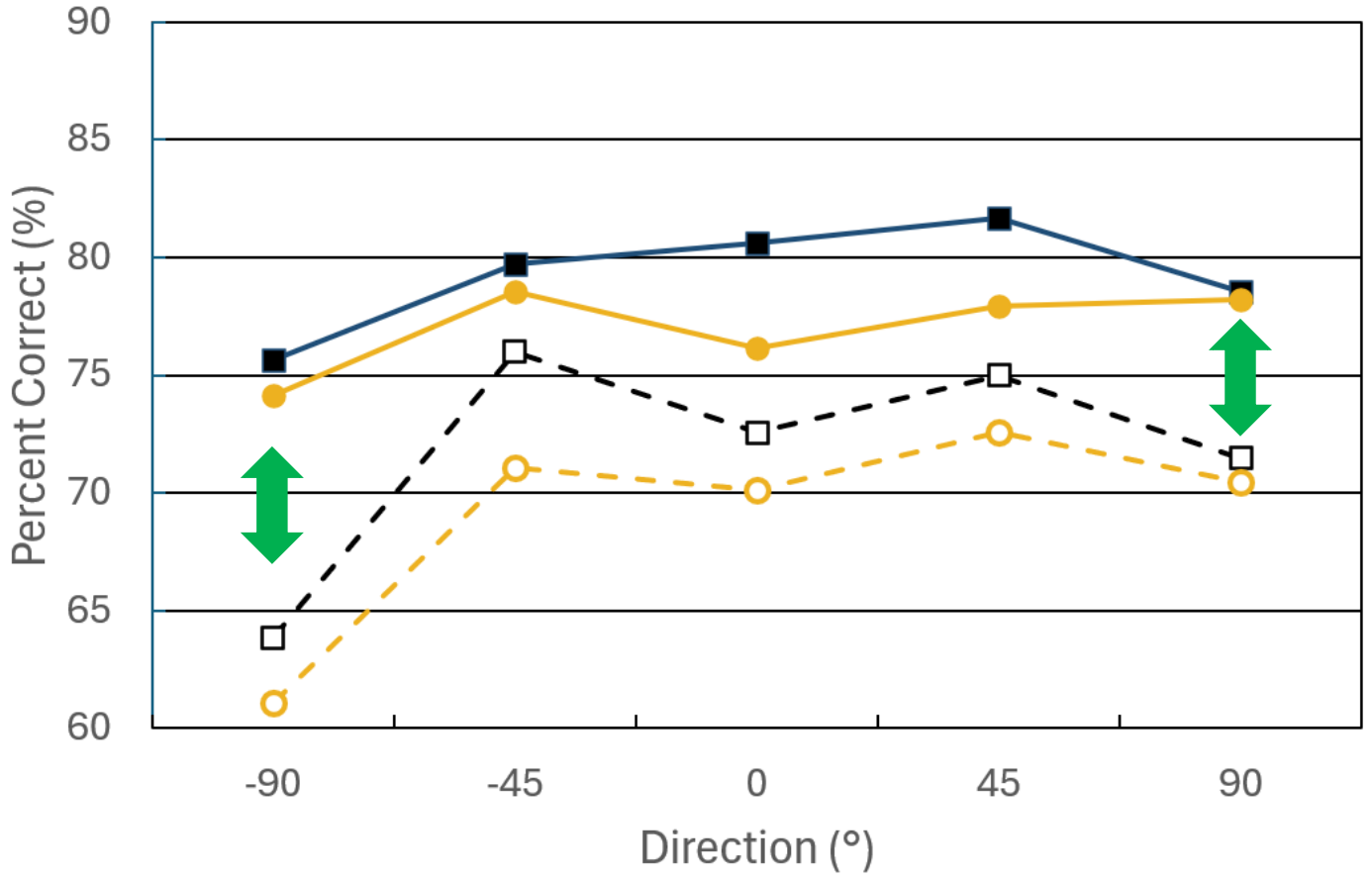
- <u>Cognitive Effect (Freq vs Rare)</u>:
  - SPIN - Frequent was better than Rare
    - Baseline (p=0.03)
    - Session 1 (p=0.02)
    - Not Session 2 (p=0.36)
  - SSLN – comparable performance for Frequent & Rare – DNN_{NR} overcomes and negates the cognitive load
- <u>Longitudinal Effect</u>
  - Improvement Baseline to Session 2 for SSLN only
- <u>HA Crossover Effect</u>
  - No Group difference

SSST: DNN_{NR} Decreases Response Latency



- $\underline{DNN_{NR}\ Effect}$:
  - SSLN < SPIN (p<0.001)

SSST: Effects of Noise Reduction by Direction



- SSLN > SPIN (p<0.001)
- Direction (p<0.001)
- Program x Direction (p = 0.008)

SSLN | Freq

SSLN | Rare

SPIN | Freq

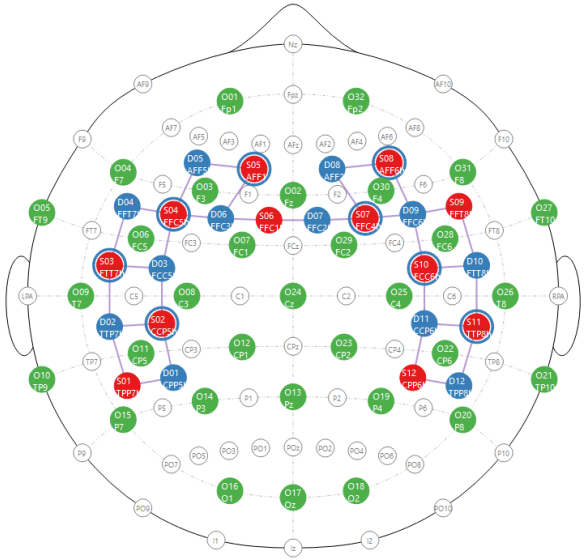
SPIN | Rare

Multimodal Neuroimaging

SSST Neurophysiological Outcome Measures

Concurrent Measures:

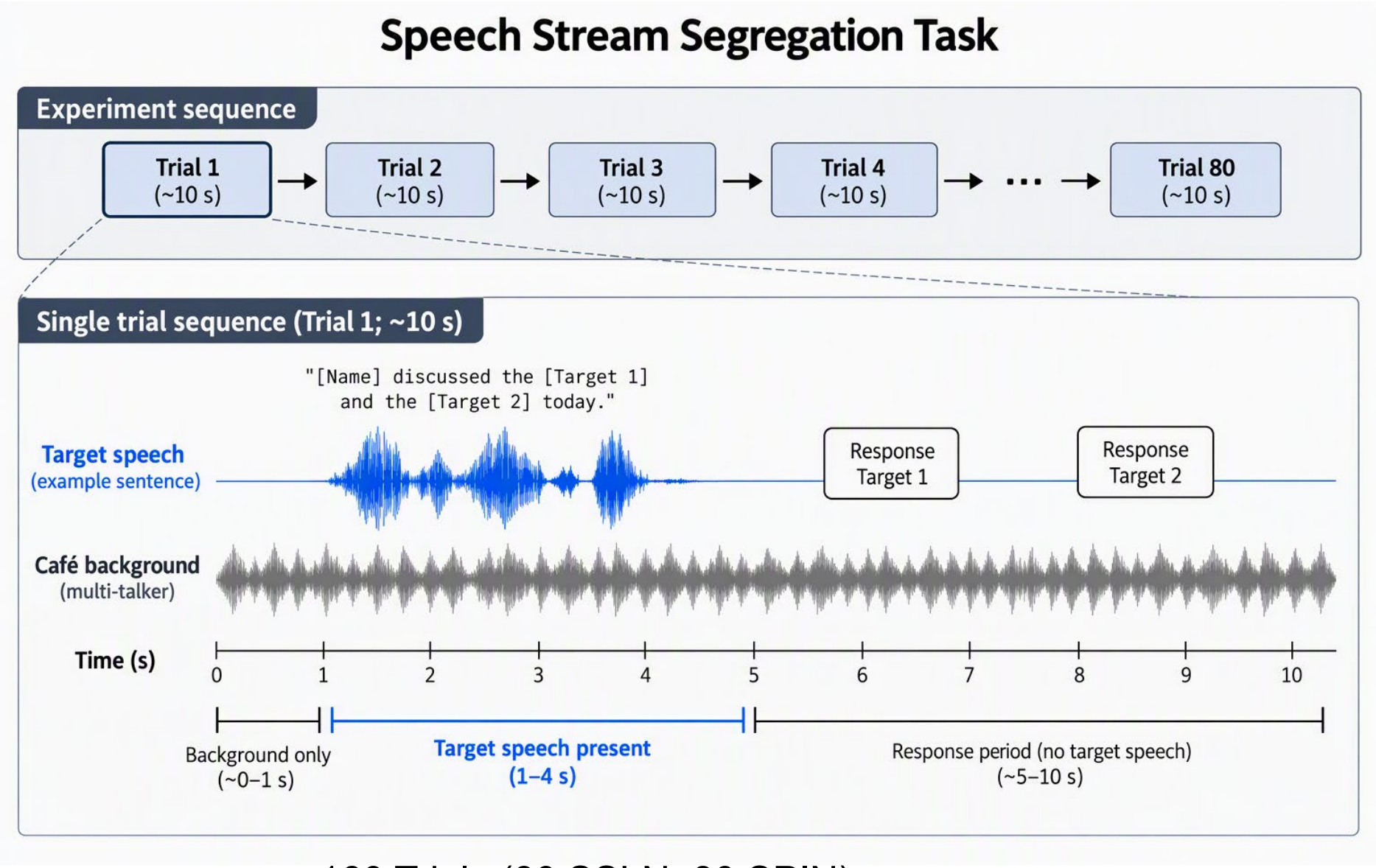
- Behavioral - % Correct, Response Latency
- Functional Near-Infrared Spectroscopy (fNIRS; NIRX)
  - 12 optode pairs, 31 channels + 8 short channels
- EEG 32-channels (Brain Vision)



fNIRS
- Source (Red)
- Detector (Blue)

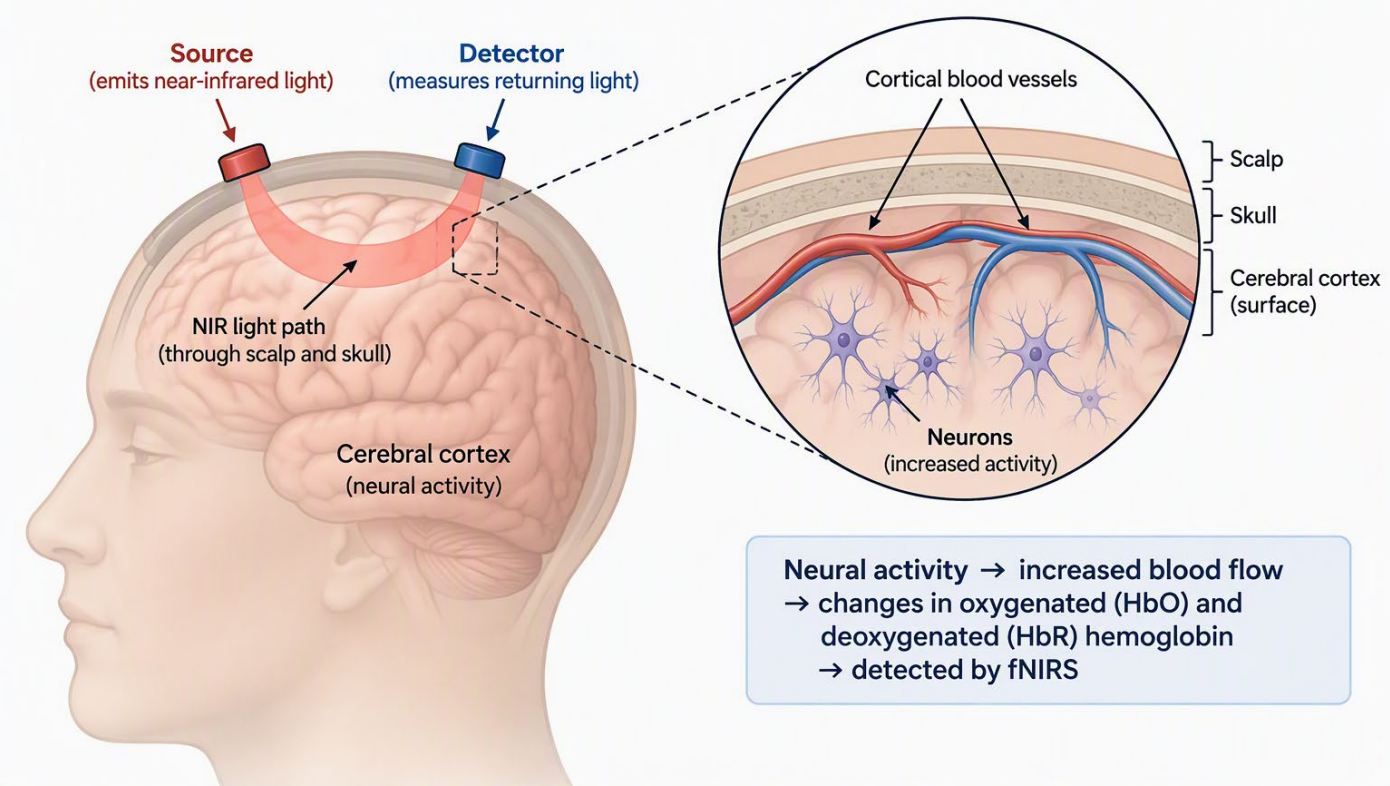
EEG - Green





- 160 Trials (80 SSLN, 80 SPIN)
- Target word frequency randomized by trial

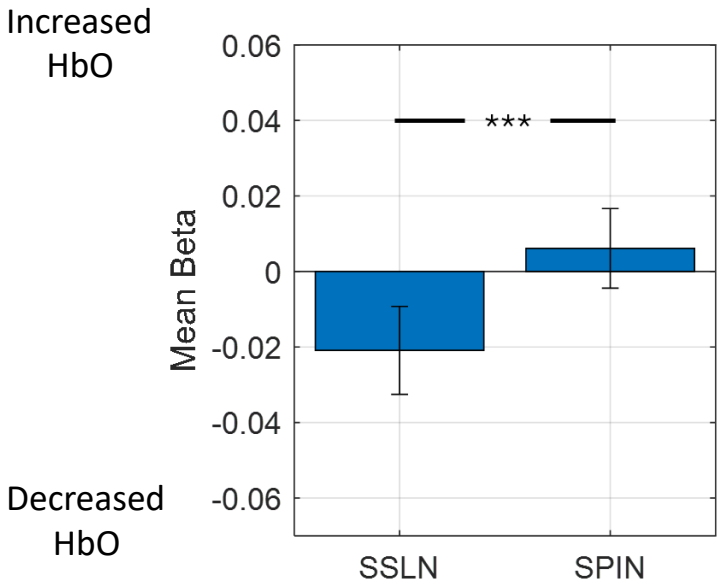
Functional Near Infrared Spectroscopy (fNIRS)





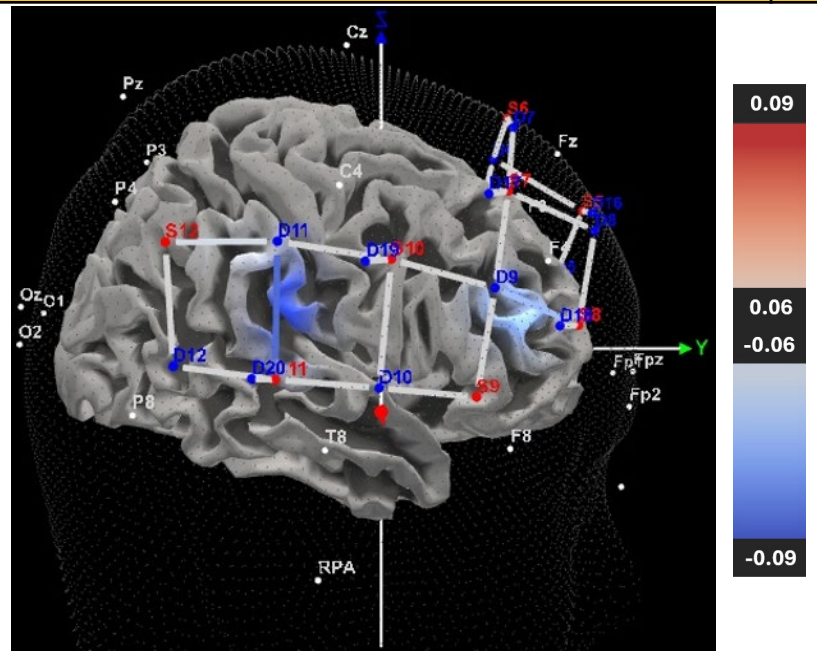
SSST – fNIRS: DNN_{NR} Reduces Hemodynamic Response

fNIRS GLM HbO	Right Hemisphere	Left Hemisphere



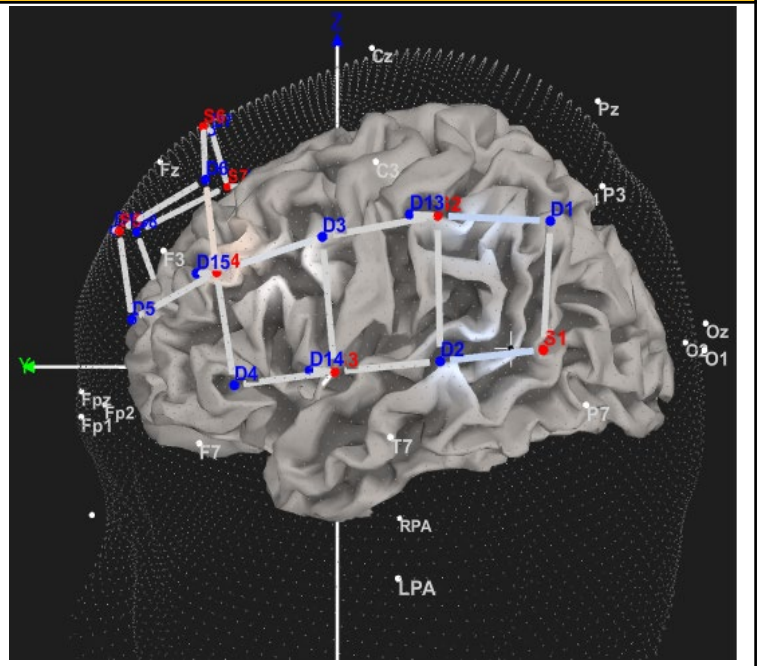
Collapsed across 3 sessions
GLM - Mixed-effects model:

- **DNN_{NR} Effect SSLN < SPIN** (p<0.001)



- Dorsolateral Prefrontal Cortex (DLPFC)
- Supramarginal Gyrus

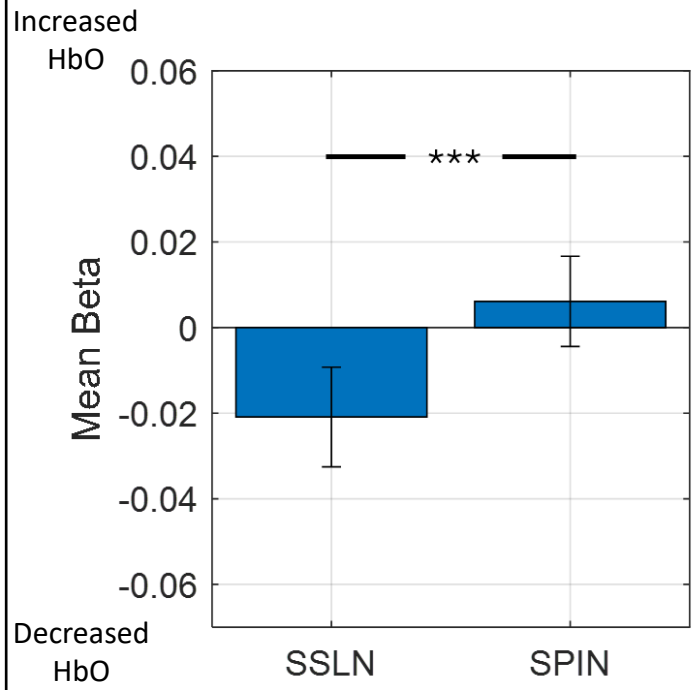
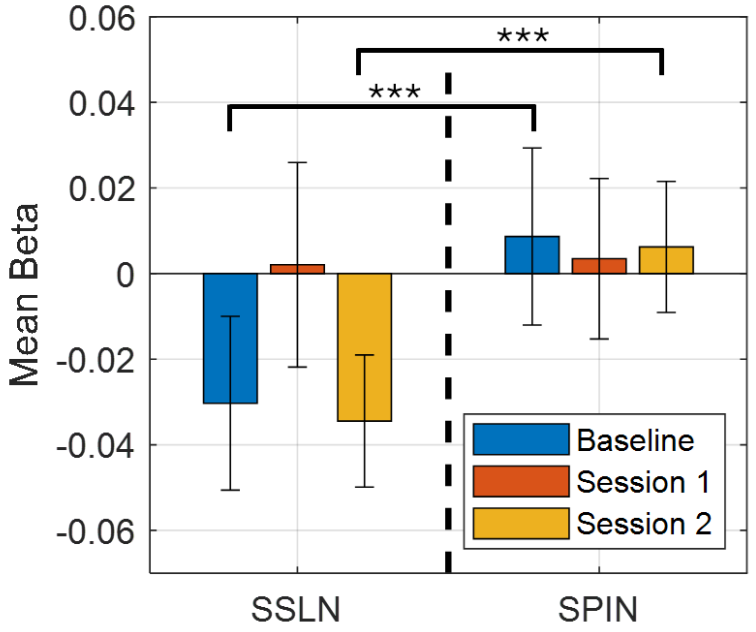
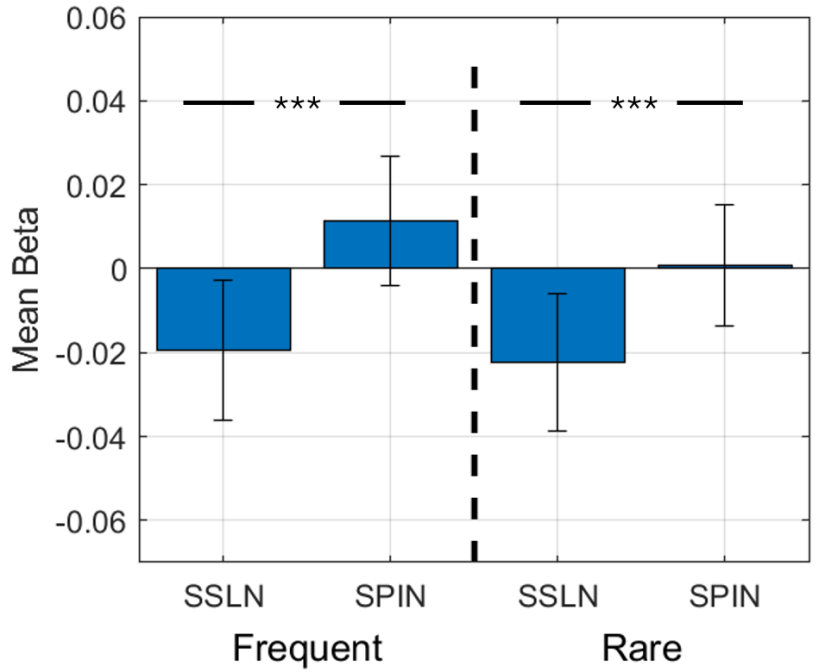
- Cognitive & Linguistic processing areas



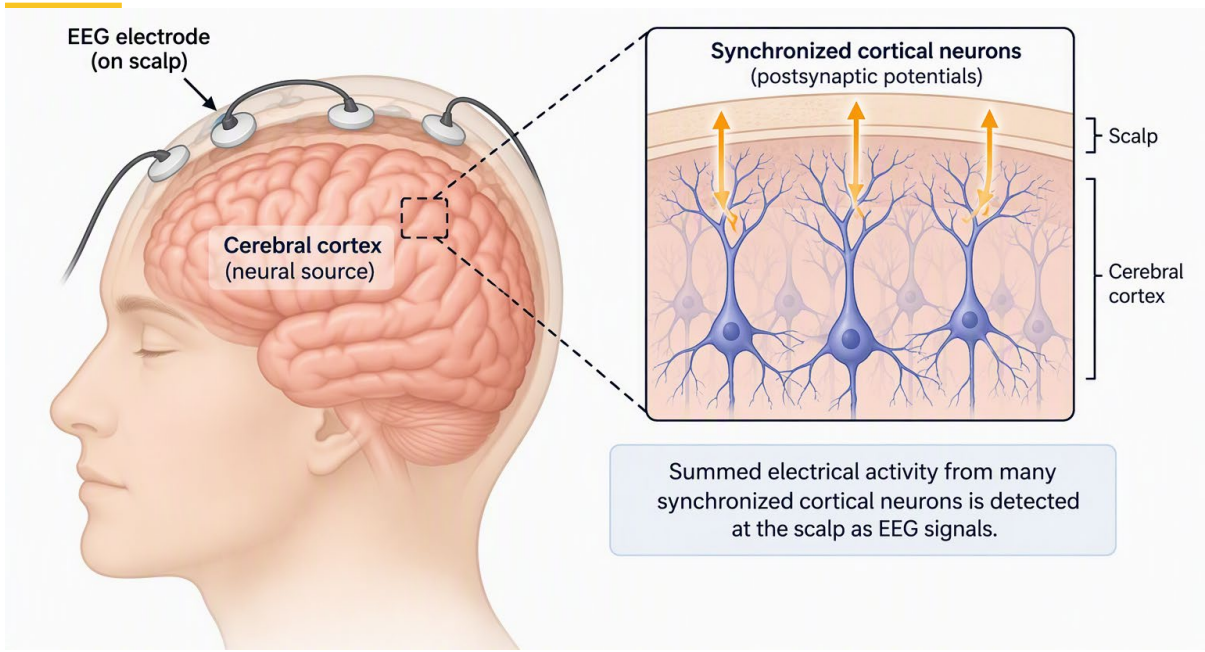
- Superior Temporal Gyrus
- Auditory Cortex

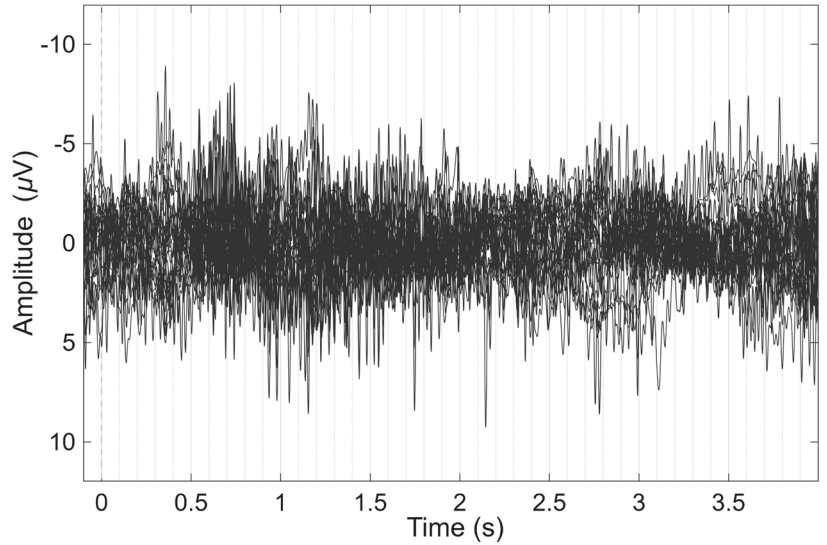
- Auditory processing areas

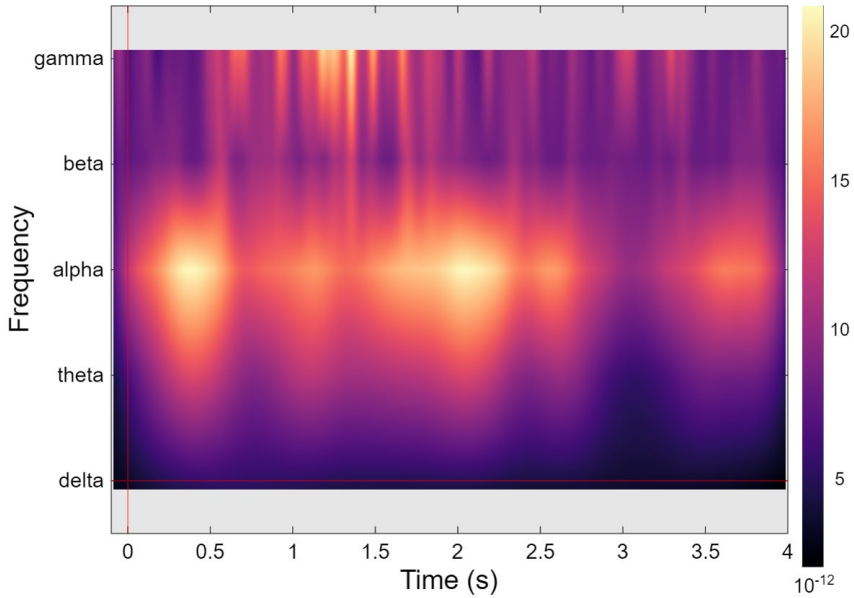
SSST – fNIRS: DNN_{NR} Reduces Hemodynamic Response

Overall	Session Effect	Cognitive Effect
		

Electroencephalography (EEG)







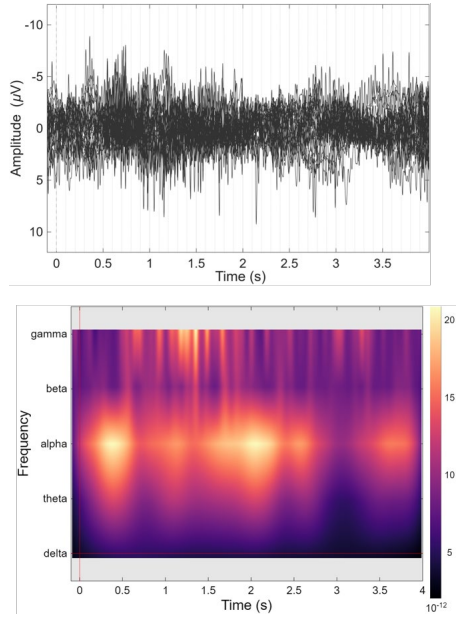
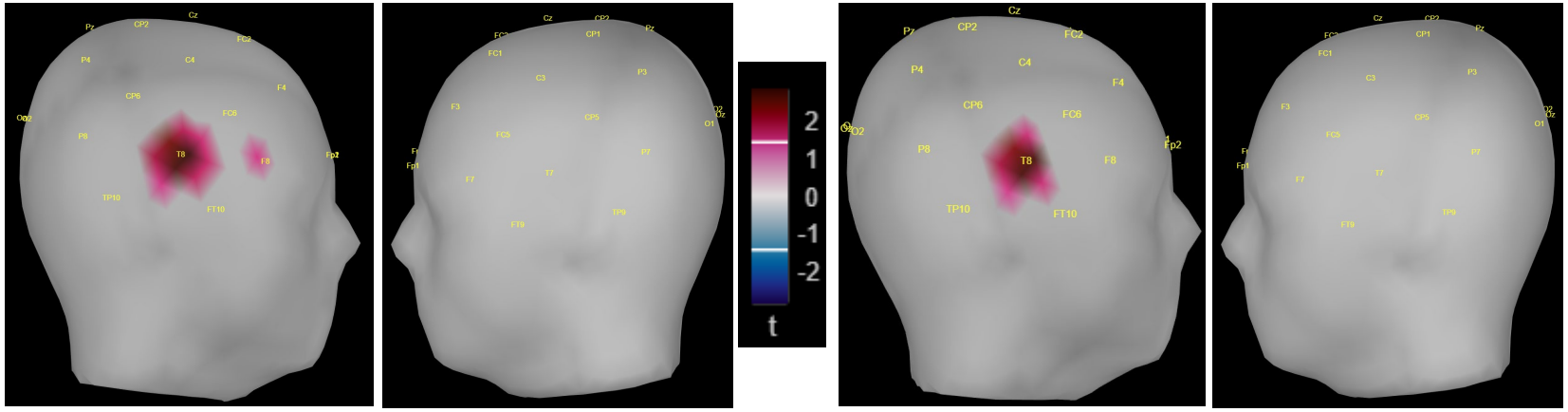
- **Time-frequency analysis of Neural Oscillations** - rhythmic fluctuations in neural populations reflect complex function including attention, decision making, inhibition of interference, auditory and speech encoding.

Neural Oscillations by Frequency Band

δ	**Delta**	**~0.5–4 Hz**	Deep sleep, slow cortical activity; prosodic and phrasal timing
θ	**Theta**	**~5–7 Hz**	Associative memory and cognitive control; syllabic parsing
α	**Alpha**	**~8–13 Hz**	Attention and sensory inhibition; listening effort
β	**Beta**	**~14–30 Hz**	Active/selective attention; target-speech processing
γ	**Gamma**	**~30+ Hz**	Acoustic/phonemic analysis; perceptual and cognitive processing

Important: Interpretation is context-dependent, representing complex network dynamics and not a fixed biomarker of a single mental operation.

SSST – EEG: DNN_{NR} Increases Oscillation Spectral Power
All 3 Sessions

Time-Frequency Analysis	Alpha (8-13 Hz)	Beta (14 – 29 Hz)
 **Paired t-tests:** • **DNN_{NR} Effect SSLN > SPIN** ($p < 0.05$)	 • Superior Temporal Gyrus • Inferior Frontal Gyrus • Active inhibition of irrelevant sensory information, facilitating selective attention.	• Superior Temporal Gyrus • Active/selective attention; target-speech processing

Summary & Conclusions

- SSLN (DNN_{NR}) relative to SPIN (Traditional NR and Dmic) conditions leads to altered **auditory perception** in experienced hearing aid users.
  - LEAP > 3:1 preference for SSLN over SPIN while actively participating in conversation
  - SSST Behavior shows:
    - **Immediate 6 to 10% improvement** in speech-in-noise performance with **reduced cognitive load and longitudinal improvement over time** (~ 2 mos.)
    - **Immediate reduction** in response latency associated with decreased cognitive load

Summary & Conclusions

- SSLN (DNN_{NR}) relative to SPIN (Traditional NR and Dmic) conditions leads to altered **neural processing** in experienced hearing aid users.
    - fNIRS shows an **immediate and longitudinal reduction in neural energy demand** in auditory, cognitive, and language processing regions of cortex in both hemispheres – markers of **neural plasticity, improved sensory processing, and reduced cognitive effort** with DNN_{NR}.
    - EEG shows **increased Alpha and Beta activity** in auditory, cognitive and language processing regions of cortex supporting **improved inhibition** of distracting input**, improved selective attention**, and **reduced cognitive effort** with DNN_{NR}.

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Thank you!

Questions?