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Using objective measures to reveal listening effort in cochlear implant listeners

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Introduction

- Cochlear implant (CI) listeners experience elevated listening effort [1,2], resulting in fatigue, compared to normal hearing (NH) listeners.
- Pupils dilate more when performing cognitive tasks [3] or speech perception tasks [4] that require more effort.
- Functional near-infrared spectroscopy (fNIRS) measures oxygen-metabolism in the cerebral blood flow, thus, indirectly revealing cortical neural activity [5].
- Cortical responses in the inferior frontal gyrus (IFG) are reported to be related to attentional and effortful listening of degraded speech [6,7].
- The frontal eye field (FEF) is involved in oculomotor activity such as eye gaze and pupil dilation [8], and also in attentional network [9].

Study question: Will self-reported difficulty levels under different conditions positively relate to changes in fNIRS responses in regions of interest (ROIs, IFG and FEF), and pupil dilation in CI listeners and NH listeners with CI simulation?

Methods: Participants and Stimuli

Participants

- NH listeners: 21 native English speakers (13 females);
  age (mean ± SD): 22.0 ± 2.5 years
- Bilateral CI (BiCI) listeners: 5 native English speakers
  age (mean ± SD): 42.8 ± 21.2 years; duration of BiCI use: 9.4 ± 3.6 years

Stimuli and Conditions

- AuSTIN sentences [10], e.g., *The TV show was funny*, presented through a loud speaker at the front (at 1.5 m away).
- **Listening Conditions** (Table 1)

NH Listeners	BiCI Listeners
Portions shuffled (S, last 3 words)	N/A
8-channel Vocoded (V)	Unprocessed Speech (U)
Shuffled-vocoded (SV)	Shuffled (S)
Vocoded-Interrupted (VI, cycle: 16 Hz)	Interrupted

- **fNIRS and pupillometry measures** were obtained in separate sessions.

Methods: fNIRS

Data Collection

- fNIRS data were collected during several (see Table 1) 8-min testing sessions, using a pseudo-random block-design (Fig 1).
- In total, 10 blocks of data were collected per listening condition.

Fig 1. fNIRS data collection. Left: diagram of data collection; middle: testing aetup with NIRx (NIRScout); right: fNIRS montage). Red (S) for light sources (n=16), blue (D) for detectors (n=16), and green for short channels (n=8).

Task 1: Detection Task

- Blocks of 5 sentences were presented; after each block, a sentence was shown on the monitor. Participants then pushed the left (*yes*) or right (*no*) mouse button to indicate whether the sentence appeared in the prior block (Fig 1).

Task 2: Difficulty Score

- After each session, participants reported the task difficulty level of each listening condition from 0-10 using a computer interface.

Methods: Pupillometry

Data Collection

- Pupillometry data were collected using a block design (Fig 2), with 5 trials per block and different hearing conditions presented in a randomized order.
- In total, 25 trials (5 blocks x 5 trials per block) were collected for each condition.

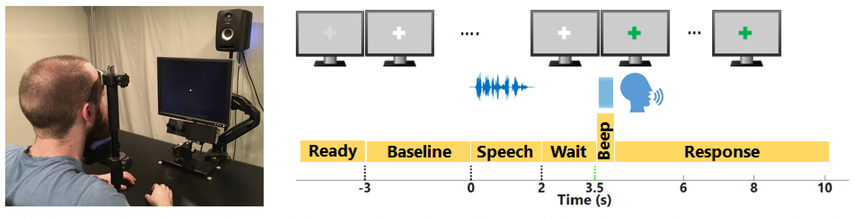

Fig 2. Pupillometry data collection. Left: testing setup with eye tracker (SR Eyelink); right: diagram of data collection.

Task 1: speech perception

- Participants listened to and verbally repeated back a 'correct' sentence based on words they heard, with their eyes fixed on the monitor (Fig 2).
- Accuracy was scored as the percentage of whole sentences repeated correctly.

Task 2: task difficulty reporting

- After each session, participants reported the task difficulty level of each listening condition from 0-10.

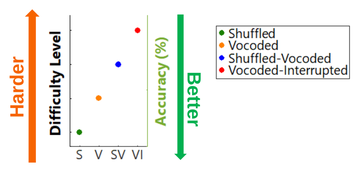

Fig 3. Prediction of task difficulty and speech perception in NH listeners.

Prediction and Hypothesis

Listening effort

We predicted that changes in fNIRS responses in the IFG and FEF, and pupil dilation would positively relate to self-reported difficulty level, indicating objective measures of listening effort as a function of task difficulty level.

Speech Perception

We hypothesized that fNIRS responses in the left auditory cortex (LAC) would be positively related to listeners' % correct on speech perception, as LAC is thought to be directly involved in processing speech information.

Results in NH listeners (N=21)

Reported difficulty level and speech perception

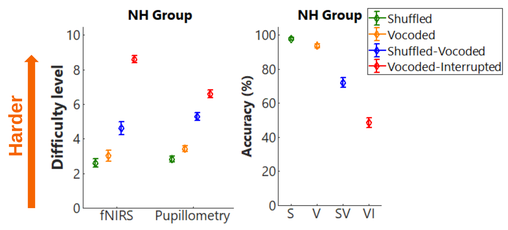

Fig 4. NH listeners' reported difficulty level and speech perception. Error bars are standard error of means (SEMs).

Difficulty level:

The patterns of reported difficulty levels across 4 conditions from ***fNIRS*** and ***pupillometry*** sessions are consistent

Speech perception:

Speech perception (measured in ***pupillometry*** session) decreased as reported task difficulty increased $\chi^2(3) = 56.63$, $p < .001$

fNIRS

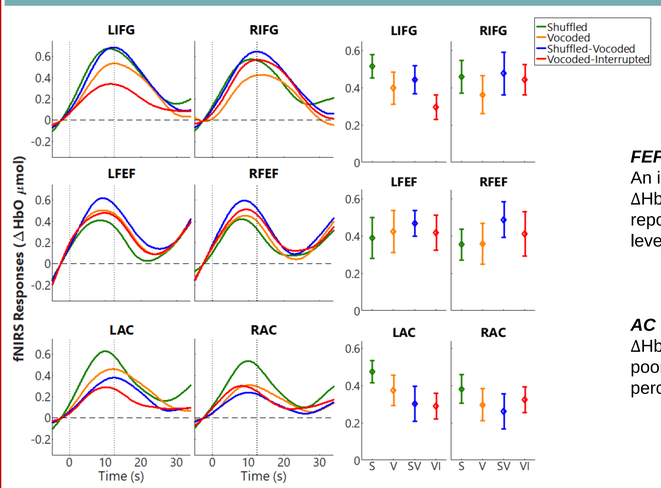

Fig 5. Group mean of ΔHbO responses in NH listeners at left (L) and right (R) IFG, FEF and AC when responding to speech sentences under 4 conditions. Error bars are SEMs.

FEF (frontal eye field)
An increasing trend of ΔHbO with higher reported task difficulty level

AC (auditory cortex)
ΔHbO decreased with poorer speech perception score

Pupillometry

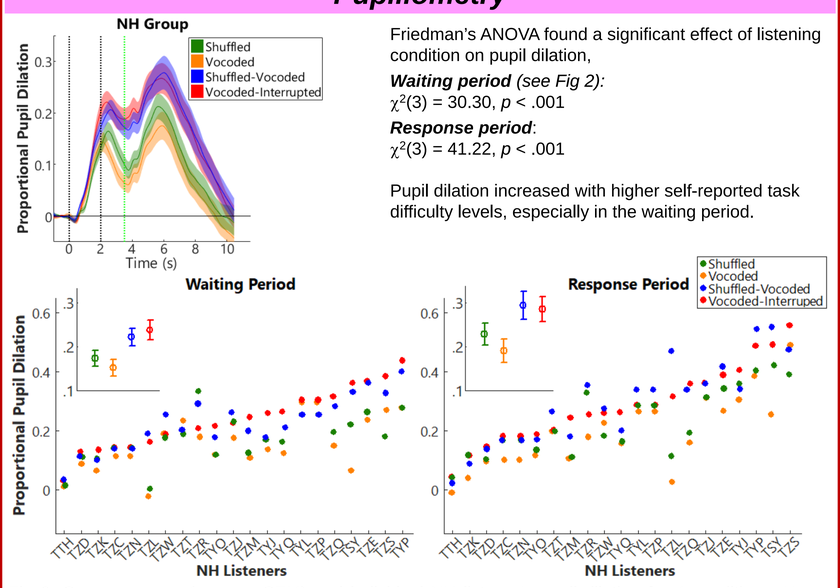

Fig 6. Group average (mean ± SEM) and individual NH listener's pupil dilation for 4 conditions. Upper panel: 2 black vertical dash lines are speech onset and offset; the green line is the beginning of response period. Error bars are SEMs.

Friedman's ANOVA found a significant effect of listening condition on pupil dilation,

Waiting period *(see Fig 2)*:
$\chi^2(3) = 30.30$, $p < .001$

Response period:
$\chi^2(3) = 41.22$, $p < .001$

Pupil dilation increased with higher self-reported task difficulty levels, especially in the waiting period.

Results in BiCI listeners (N=5)

Reported difficulty level and speech perception

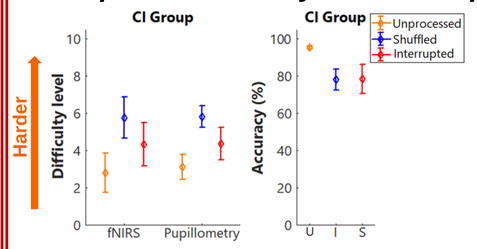

Fig 7. BiCI listeners' reported difficulty level and speech perception. Error bars are SEMs.

Difficulty level:

The patterns of reported difficulty levels across 3 conditions from ***fNIRS*** and ***pupillometry*** sessions are consistent
$\chi^2(2) = 7.60$, $p = .022$
$\chi^2(2) = 8.82$, $p = .012$

fNIRS

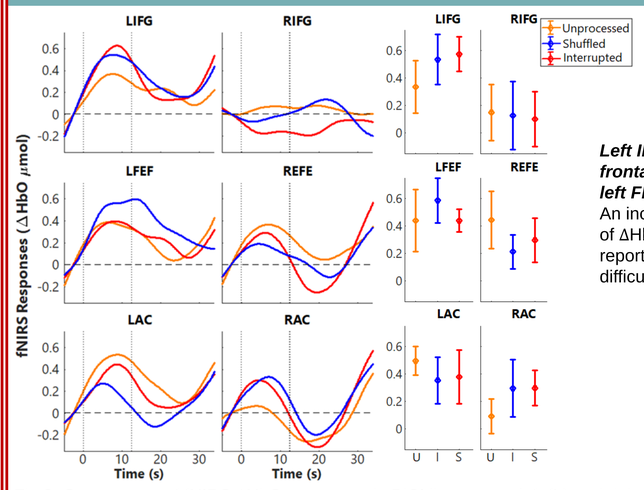

Fig 8. Group mean of fNIRS ΔHbO responses in BiCI listeners at left (L) and right (R) IFG, FEF and AC when responding to speech sentences under 3 conditions. Error bars are SEMs.

Left IFG (inferior frontal gyrus) and left FEF
An increasing trend of ΔHbO with higher reported task difficulty level

Pupillometry

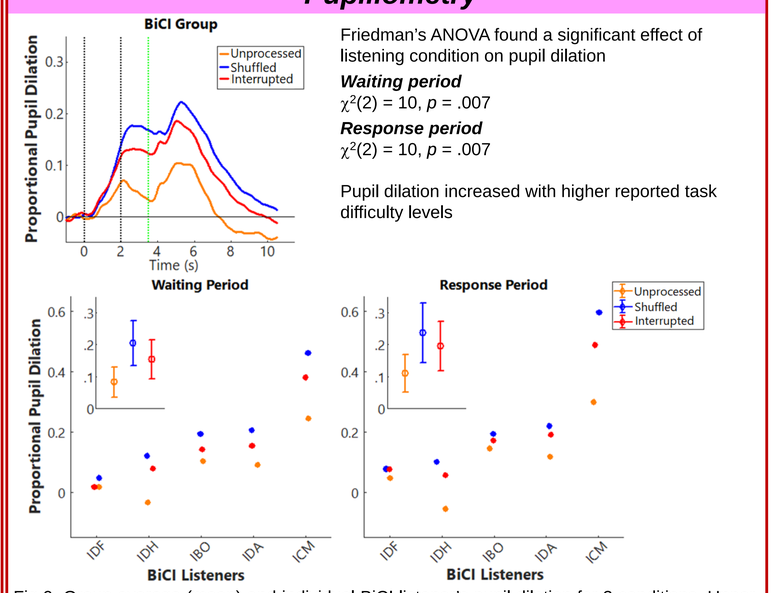

Fig 9. Group average (mean) and individual BiCI listener's pupil dilation for 3 conditions. Upper panel: 2 black vertical dash lines are speech onset and offset; the green line is the beginning of response period. Error bars are SEMs.

Friedman's ANOVA found a significant effect of listening condition on pupil dilation

Waiting period
$\chi^2(2) = 10$, $p = .007$

Response period
$\chi^2(2) = 10$, $p = .007$

Pupil dilation increased with higher reported task difficulty levels

Summary

NH listeners

- Self-reported difficulty levels across 4 conditions in fNIRS (Fig 4) and pupillometry sessions were consistent (Fig 7), which confirmed our predictions (Fig 3).
- With higher reported difficulty levels, there was an increasing trend of fNIRS responses in the bilateral FEF (Fig 5) corresponded with greater pupil dilation (Fig 6), supporting our predictions about objective measures and listening effort.
- fNIRS responses in the AC (especially the left, Fig 5) decreased with poorer speech perception (Fig 4), supporting our hypothesis about LAC being sensitive to speech intelligibility.

BiCI listeners

- Pupil dilation increased with higher self-reported difficulty levels, supporting our predictions. Though BiCI listeners reported the shuffled rather than the interrupted condition as the hardest, unlike the NH listeners.
- Pupil dilation in BiCI listeners' showed similar patterns with NH listeners for corresponding conditions, especially in response period (compare Fig 9 and Fig 6).
- More data will be collected to explore the fNIRS measures in BiCI listeners.

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