Quality Estimation of Human Frequency-Following Responses

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INTRODUCTION

- The frequency-following response (FFR) is widely used to study speech and music perception, auditory processing disorders, and neural plasticity. It captures sustained neural phase-locking to sound but remains challenging to interpret due to its small amplitude and susceptibility to EEG noise (Gorina-Careta et al., 2022; Krizman & Kraus, 2019).
- FFR recordings typically use fixed-sweep averaging to enhance the signal-to-noise ratio (SNR). However, this does not guarantee response quality, as neural synchrony and EEG noise vary across individuals and sessions. This variability limits clinical and research applications.
- A statistical metric is needed to assess FFR quality. A similar challenge in auditory brainstem response (ABR) recordings led to the Fsp algorithm (Don et al., 1984; Elberling & Don, 1984), which evaluates response reliability. Since ABR and FFR share characteristics, adapting Fsp for FFR could provide an objective quality assessment.
- The algorithm can be expressed: $F_{sp} = \frac{VAR(\bar{S})}{VAR(SP)}$
  - Where VAR(S) is the variance of the averaged signal,
  - VAR(SP) is the variance of the SP values across N number of sweeps
- We hypothesize that a robust FFR quality metric would enable:
  1. More reliable interpretation of responses
  2. Adaptive control over sweep numbers
  3. Enhanced automation of data collection

METHODS

Participants
- 15 college students (22.7 ± 1.7 years old) with normal hearing

Acoustic Stimuli
- ABR:
  - Rarefaction clicks, 33.7 clicks/s
  - 0, 20, 40, 60 dB nHL to the right ear
  - Pre-control and post-control conditions
- FFR
  - An English vowel /i/ with a rising frequency contour (F0 ranging from 102 to 140 Hz)
  - The stimulus has a duration of 150 ms (experimental condition), with a silent interval of 150 ms (control condition) at 60 dB nHL to the right ear.

EEG Recordings
- 3 gold-plated surface recording electrodes
- 8000 accepted sweeps for each recording

Fsp Parameters
- Time window
  - ABR: 1-11 ms for high intensities, 4-14 ms for low intensities and control conditions
  - FFR: 10-150 ms (experiment) and 160-300 ms (control)
- SP locations
  - ABR: 2, 3, 4, 5, 6, 7, and 8 ms
  - FFR: 20, 40, 60, 80, 100, 120, and 140 ms

Statistical Analyses
- ABR: Three-way ANOVA (intensities x N sweeps x SP locations)
- FFR: Three-way ANOVA (conditions x N Sweeps x SP locations)

RESULTS

EEG Recording

Figure 1. Gold plate electrodes were placed on the high forehead, right mastoid, and low forehead to pick up neural activity elicited from hearing a speech stimuli through an insert ear tip placed in the right ear. Participants were encouraged to remain relaxed and still throughout testing.

Fsp Algorithm – An Example

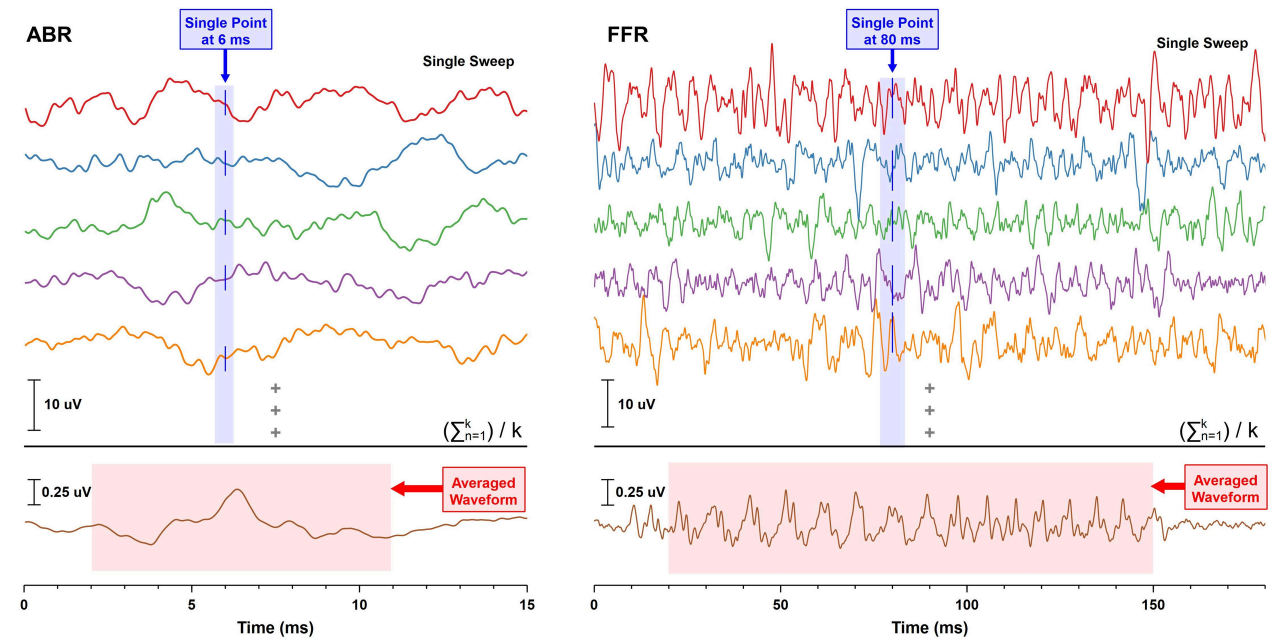

Figure 2. Quality Estimation of ABR and FFR Recordings. This figure illustrates the application of the Fsp algorithm to auditory brainstem response (ABR) and frequency-following response (FFR) recordings. In the ABR panel, single sweeps are shown in the upper portion, with a selected point at 6 ms used to estimate background noise variance. The lower portion displays the averaged waveform for estimating signal variance. The FFR panel follows a similar structure, with a point selected at 80 ms. Fsp values are computed as the ratio of signal variance to background noise variance, providing a quantitative measure of response quality.

Assumption Check – Gaussian Distribution

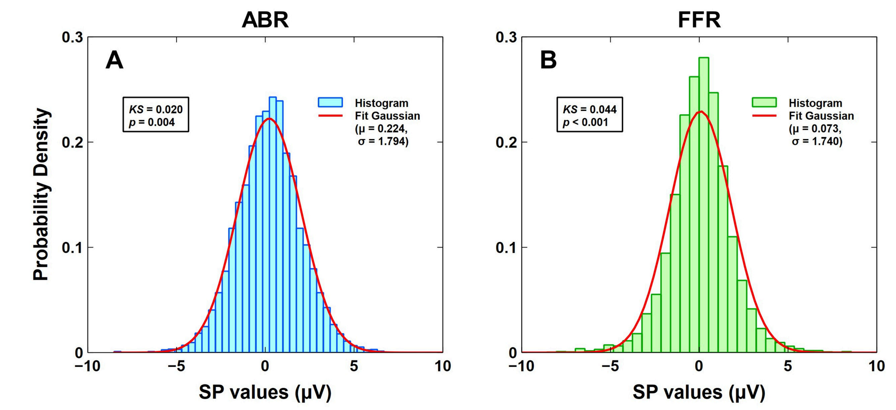

Figure 3. Assumption check for Gaussian distribution of SP values in ABR (A) and FFR (B) recordings.

SP Location – No Effect

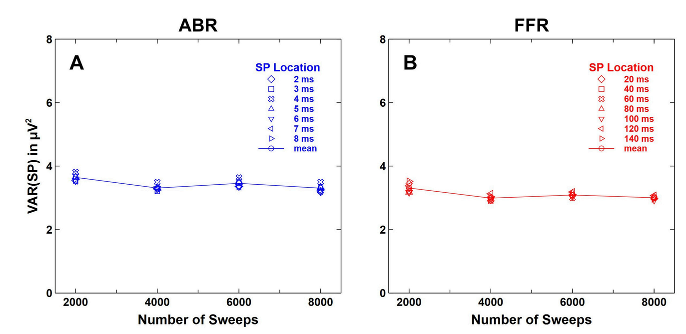

Figure 4. Estimation of background noise variance across different SP locations for ABR (A) and FFR (B).

ELECTROPHYSIOLOGICAL ASSESSMENT

Response Waveforms

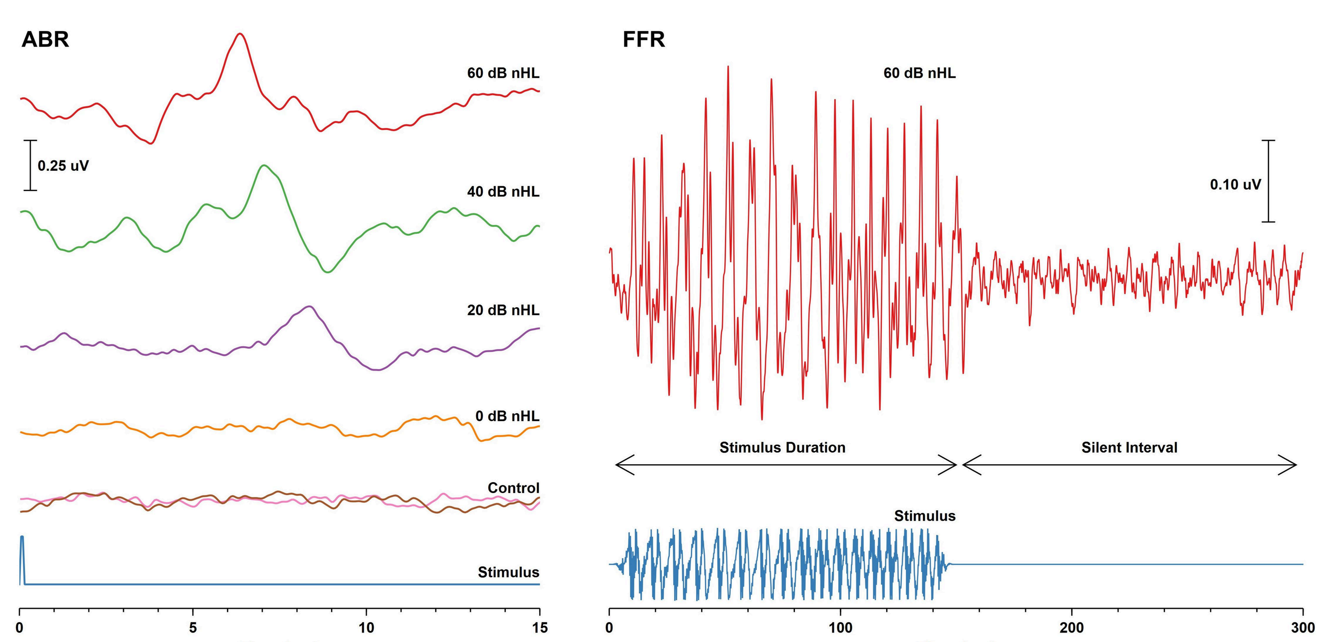

Figure 5. Response Waveforms of ABR and FFR. The left panel displays ABR waveforms recorded from a participant at varying stimulus intensities. A distinct wave V is evident at higher intensities (60, 40, and 20 dB nHL) but absent at 0 dB nHL and in control conditions, confirming the expected intensity-detectability relationship. The right panel shows an FFR waveform at 60 dB nHL, exhibiting a periodic structure during stimulus presentation, indicating neural phase-locking. In contrast, the silent interval contains only background noise, distinguishing evoked responses from spontaneous activity.

Quality Estimation

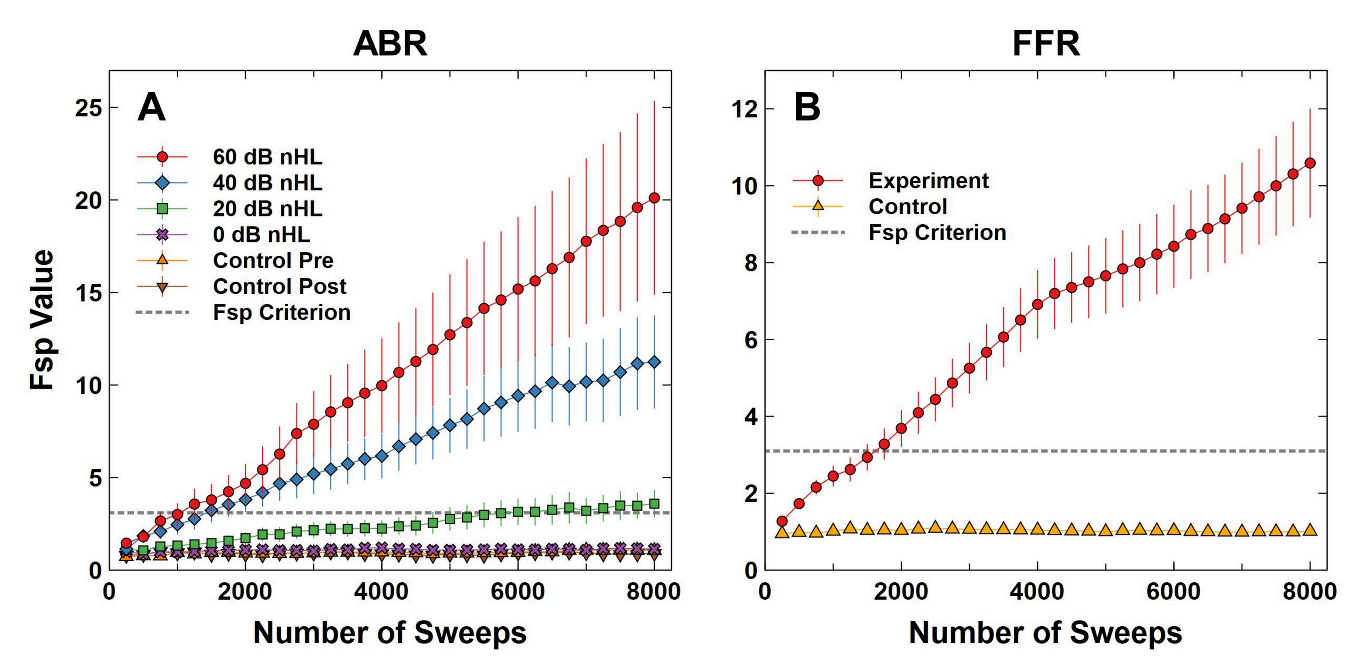

Figure 6. The Fsp algorithm uses a cutoff value of 3.2 for detecting the response. For ABR, it is confirmed that the algorithm is effective for the tested intensities of 60, 40, and 20 dB nHL. Despite FFR response being significantly smaller than ABR response, the Fsp algorithm was successfully able to detect the presence of a response at 60 dB nHL. Control conditions for both measures confirmed accurate results.

DISCUSSION

The Fsp algorithm objectively analyzes ABR and FFR to assess response quality. Fsp values increase as more sweeps accumulate when a neural response is present, making it an automated, observer-independent method. This approach reduces subjectivity compared to traditional visual waveform inspection.

Comparison with Traditional Methods
- Traditional methods rely on:
  - Peak amplitude analysis, which is prone to noise-related errors.
  - Visual inspection, which introduces subjectivity and variability.
- The Fsp algorithm offers a statistical, objective approach for response detection.
- Unlike post-hoc traditional methods, Fsp enables real-time monitoring.
- Central Limit Theorem (Howell, 2009): As sweeps increase, the distribution of values normalizes, improving noise variance estimation.

Clinical & Research Applications
- Clinical use:
  - Enhances neonatal hearing screening and assessments for individuals with communication disorders.
- Research benefits:
  - Strengthens FFR studies on auditory processing (dyslexia, aging, bilingualism).
  - Optimizes data collection with real-time monitoring.

Limitations & Future Directions
- Needs broader testing beyond young adults with normal hearing.
- Applicability to diverse stimuli (speech, music) should be explored.
- Clinical adoption requires real-world validation and user-friendly software.

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