AIDED ENVELOPE FOLLOWING RESPONSES TO FREQUENCY-SPECIFIC AND SPEECH STIMULI AS PREDICTORS OF HEARING AID BENEFIT IN CHILDREN WITH SENSORINEURAL HEARING LOSS

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CERTIFICATE

This is to certify that this dissertation entitled **"Aided Envelope Following Responses to Frequency-Specific and Speech Stimuli as Predictors of Hearing Aid Benefit in Children with Sensorineural Hearing Loss"** is a bonafide work submitted as part of fulfilment of the degree of Master of Science **(Audiology)** of the student with Registration Number **P01II24S023033**. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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CERTIFICATE

This is to certify that this dissertation entitled "**Aided Envelope Following Responses to Frequency-Specific and Speech Stimuli as Predictors of Hearing Aid Benefit in Children with Sensorineural Hearing Loss**" has been prepared under my supervision and guidance. It is also being certified that this dissertation has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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DECLARATION

This is to certify that this dissertation entitled **"Aided Envelope Following Responses to Frequency-Specific and Speech Stimuli as Predictors of Hearing Aid Benefit in Children with Sensorineural Hearing Loss"** is the result of my own study under the guidance of Dr. Srikar Vijayasarathy., Assistant Professor of Audiology, All India Institute of Speech and Hearing, Mysuru and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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Abstract

Children with sensorineural hearing loss depend on hearing aids not only for access to sound but for language development, yet behavioral verification of amplification benefit is often unreliable in young children, particularly those with severe-to-profound loss. This study evaluated the clinical utility of a hybrid Envelope Following Response (EFR) protocol that paired frequency-specific amplitude-modulated (AM) tonal stimuli with an ecologically valid speech-like token to objectively assess hearing aid benefit in pediatric populations. Twenty-six children aged 3–5 years with bilateral congenital sensorineural hearing loss were enrolled and assigned to two groups according to degree of hearing loss: moderate-to-moderately-severe (n = 13) and severe-to-profound (n = 13). Aided EFR amplitudes were recorded under free-field conditions, and their associations with aided audiometric thresholds and language development were examined using Pearson correlations and simple linear regression. In the moderate-to-moderately-severe group, EFR amplitudes did not predict aided thresholds at any frequency, a pattern consistent with a ceiling effect under good aided audibility. In the severe-to-profound group, however, frequency-matched EFR amplitudes were robust predictors of aided thresholds across all carrier frequencies, accounting for up to 66% of variance at 4000 Hz (AM tone) and 60% at 2000 Hz (speech). AM-tone and speech EFRs proved complementary rather than redundant-tones outperformed speech at 4000 Hz while speech outperformed tones at 2000 Hz, supporting a combined hybrid approach. EFR amplitudes in the severe-to-profound group also correlated positively with both receptive and expressive language age, suggesting that neural encoding quality reflects broader communicative development. These findings support the use of a hybrid EFR protocol as a feasible, frequency-specific, objective tool for verifying hearing aid benefit in children with severe-to-profound hearing loss, the population for whom behavioral verification is most difficult and the stakes are highest.

Keywords: *envelope following response, hearing aids, sensorineural hearing loss, pediatric audiology, hearing aid benefit, speech-evoked EFR, amplitude-modulated tones, hybrid EFR protocol, language development*

Chapter I

Introduction

Hearing loss is one of the most prevalent chronic health conditions worldwide, affecting individuals across all age groups, with particularly significant consequences when present early in life. Globally, an estimated 430 million people live with disabling hearing loss, and this number is expected to rise in the coming years. In the pediatric population, approximately 2 out of every 1,000 infants are born with permanent congenital hearing loss (Joint Committee on Infant Hearing, 2019). Early auditory deprivation during critical periods of neural development can adversely affect speech and language acquisition, leading to long-term challenges in communication, academic performance, and social integration (Easwar et al., 2023).

Hearing aids (HAs) are the primary rehabilitative intervention for children with sensorineural hearing loss, enabling access to auditory input across varying degrees of impairment. However, amplification alone does not guarantee optimal auditory outcomes. Many children continue to experience difficulty in complex listening environments such as background noise and reverberation. Additionally, variability in auditory outcomes arises due to differences in hearing loss characteristics, neural encoding ability, and hearing aid signal processing. These factors highlight the need for reliable methods to evaluate hearing aid benefit in pediatric populations (Easwar et al., 2015).

Behavioral measures such as aided audiograms, speech perception testing, and functional listening assessments are traditionally used to evaluate hearing aid benefit. While these methods provide valuable insights into real-world auditory performance, their reliability in young children is often limited due to developmental factors, reduced attention span, and inconsistent responses. Consequently, obtaining accurate and repeatable behavioral data remains a challenge in pediatric audiology.

Objective electrophysiological measures have therefore been explored as alternatives for assessing auditory function. Cortical auditory evoked potentials (CAEPs) provide information about cortical-level processing and have been used to evaluate aided audibility in children (Golding et al., 2009; Sharma et al., 2011). However, these responses are influenced by attention, arousal state, and sleep, which can introduce variability in recordings (Chang et al., 2012).

In this context, Envelope Following Response measures have emerged as a promising objective tool for assessing auditory processing. EFRs reflect neural encoding of the temporal envelope of acoustic signals and can be elicited using modulated tonal or speech-based stimuli. Due to their predominantly subcortical origin, EFRs are relatively robust to variations in attention and sleep state, making them particularly suitable for use in pediatric populations (Purcell et al., 2004a).

A key advantage of EFRs lies in their ability to utilize stimuli that better represent real-world listening conditions. While frequency-specific modulated tones enable assessment of neural encoding across individual frequency regions, speech-evoked stimuli provide insight into functional processing of complex acoustic signals. The integration of these approaches offers the potential for a more comprehensive evaluation of aided auditory function.

Despite these advantages, the clinical application of EFRs for evaluating hearing aid benefit in children remains limited. In particular, there is a lack of studies investigating the combined use of frequency-specific and speech-evoked EFR measures, as well as their ability to predict functional auditory outcomes in pediatric populations.

Therefore, there is a need to explore objective, reliable, and clinically feasible methods for assessing hearing aid benefit in children with sensorineural hearing loss. A hybrid approach combining frequency-specific tonal stimuli and speech-evoked EFRs may provide a more comprehensive understanding of auditory processing and improve the prediction of hearing aid outcomes in pediatric populations.

Aim

To investigate the clinical utility of a hybrid envelope following response (EFR) protocol for objective hearing aid benefit in children with hearing loss, by combining frequency-specific tonal stimuli with ecologically valid speech stimuli

Objectives

1. To correlate measures of aided EFR for frequency-specific tonal stimuli with behavioral measures that include aided audiometric thresholds, and language development in children with moderate to moderately severe and severe to profound sensorineural hearing loss using hearing aids

2. To correlate measures of aided EFR for speech-like tokens with behavioral measures that include aided audiometric thresholds, and language development in children with moderate to moderately severe and severe to profound sensorineural hearing loss using hearing aids

3. To explore the relative predictive value of EFRs for frequency-specific amplitude modulated tones and speech stimuli in children with moderate to moderately severe and severe to profound sensorineural hearing loss using hearing aids

Chapter II

Review Of Literature

Envelope Following Responses (EFRs) are scalp-recorded electrophysiological responses that reflect the auditory system's ability to follow the temporal envelope of acoustic signals. These responses are generated through phase-locked neural activity to amplitude-modulated stimuli and speech stimuli and are believed to arise predominantly from subcortical auditory structures. EFRs have become increasingly important in audiology research, because of their ability to objectively represent neural synchrony within the auditory pathway (Dolphin & Mountain, 1992).

Interest in EFRs has grown considerably over the past few years because these responses provide insight into how the auditory system encodes speech-related acoustic information. Unlike behavioral measures, which depend on active participation from the listener, EFRs offer an objective representation of neural processing. This makes them particularly valuable in populations where reliable behavioral responses may be difficult to obtain, such as infants and young children.

Several studies have demonstrated that EFRs are sensitive to acoustically and perceptually important features of speech. One of the most important among these is the fundamental frequency of voiced speech sounds, which contributes significantly to pitch perception and voice recognition (Easwar et al., 2022). Beyond pitch-related cues, EFRs are also capable of representing temporal aspects of speech, including the periodicity envelope and temporal fine structure. These temporal cues are essential for speech understanding, especially in complex listening situations such as noisy environments (Ananthakrishnan et al., 2016)

The importance of EFRs becomes even more evident when considering their relationship with behavioral auditory performance. Previous research has demonstrated significant associations between EFR measures and psychoacoustic tasks such as gap detection and modulation detection thresholds, suggesting that neural encoding measured through EFRs closely reflects perceptual temporal processing abilities (Purcell et al., 2004a). Similarly, EFRs have been associated with individual differences in auditory nerve function and temporal coding efficiency, indicating their sensitivity to underlying neural integrity (Shinn-Cunningham et al., 2017). More recently, the studies have also shown that EFR magnitude can predict speech perception in noise, further highlighting the clinical relevance of these responses as objective indicators of functional listening ability (Mepani et al., 2021).

As evidence supporting the clinical relevance of EFRs continued to expand, researchers increasingly began exploring these responses in pediatric populations. Investigating EFRs during childhood is particularly important because auditory system maturation can substantially influence neural encoding of speech signals. Understanding how EFR characteristics develop across childhood may therefore provide valuable insight into auditory processing, speech perception, and hearing-related outcomes in children.

2.1 Envelope Following Response in pediatric population

Research investigating Envelope Following Responses in children suggests that the neural generators of these responses are primarily subcortical in origin, involving early auditory structures such as the cochlear nerve and cochlear nucleus. Studies examining different recording configurations have shown that horizontally recorded EFRs are associated with cochlear nerve activity, whereas vertically recorded responses are more closely linked to activity from the cochlear nucleus. These observations are supported by latency–frequency relationships and phase-locking characteristics comparable to those observed in auditory brainstem responses (Lucchetti et al., 2021).

Understanding the neural generators of EFRs has also helped researchers examine how effectively children encode complex speech signals at the subcortical level. Speech-evoked studies have demonstrated that school-aged children exhibit EFR amplitudes and phase coherence values comparable to those observed in adults, suggesting that encoding of temporal envelope information reaches near-adult levels by this stage of development (Easwar, Purcell, et al., 2022). These findings collectively indicate that EFRs provide valuable insight into early auditory processing mechanisms in pediatric populations.

Although school-aged children demonstrate relatively mature EFR characteristics, developmental differences become more evident during infancy. Easwar et al. (2021), in a comparison of infants and young adults, reported reduced EFR amplitude, signal-to-noise ratio, and intertrial phase coherence in infants, particularly for low-frequency stimuli. These differences became more pronounced when stimulus levels were adjusted to account for adult ear characteristics. Interestingly, infants demonstrated near adult-like phase coherence at higher presentation levels, while age-related changes in phase coherence and signal-to-noise ratio were observed during the first year of life for certain speech stimuli.

These findings suggest that maturation of EFRs is influenced not only by chronological age, but also by stimulus characteristics such as frequency and presentation level. Therefore, interpretation of developmental changes in pediatric EFRs requires careful consideration of stimulus calibration and recording conditions, particularly when responses are compared across different age groups (Easwar et al., 2023).

The influence of maturation on EFR characteristics becomes even more evident when examining response morphology and detectability across modulation frequencies. Early developmental studies have reported significant age-related differences in these measures, with more pronounced changes observed at lower modulation rates during infancy.

The research demonstrates that EFR development occurs through physiological changes which depend on both stimulus frequency and stimulus intensity, which indicates that proper stimulus conditions must be set to evaluate how developmental abilities progress (Nodarse et al., 2012).

By school age, children exhibit EFR characteristics that are largely comparable to adults for low- and mid-frequency stimuli, suggesting that neural encoding of the temporal envelope reaches functional maturity by this stage. Easwar, Purcell, et al. (2022) reported similar EFR amplitude and phase coherence between children and young adults, although some differences persist for high-frequency fricative stimuli, where amplitude variations were noted within the pediatric group.

Interestingly, maturation of EFRs is not limited to early childhood. Evidence suggests continued refinement into adulthood, with shifts in resonant peak frequencies indicating ongoing development of auditory processing mechanisms (Poulsen et al., 2007). Overall, these findings suggest that while rapid maturation occurs within the first two years of life, near-adult levels of envelope encoding for most speech-relevant frequencies are achieved by school age.

2.1.1 Influence of stimulus parameters on EFR recording in children

Stimulus characteristics play a critical role in optimizing Envelope Following Response recordings in pediatric populations. Evidence indicates that modulation frequencies in the range of approximately 80–100 Hz are most effective for eliciting robust and stable responses in children, particularly during sleep conditions (Aoyagi et al., 1993). However, some variability exists, with studies in neonates reporting a broader effective modulation range, suggesting that optimal frequencies may vary depending on age and recording conditions (Riquelme et al., 2006).

Carrier frequencies spanning the speech-relevant range (500–4000 Hz) have been successfully employed in pediatric populations, enabling assessment across low- and high-frequency regions (Riquelme et al., 2006). In terms of stimulus intensity, levels between 50 and 70 dB SPL are commonly used to obtain reliable responses, with evidence indicating that intensity-related growth functions of EFRs are comparable between infants and adults (Levi et al., 1995; Nodarse et al., 2012).

2.1.2 Reliability of EFR measures in pediatric populations

Envelope Following Response recordings demonstrate reasonable reliability in infants and children, although performance varies with age and stimulus characteristics. In school-aged children with normal hearing, EFRs show good diagnostic performance, with reported sensitivity and specificity values of approximately 77% and 92%, respectively (Easwar, Purcell, et al., 2022). In early infancy, responses are present from as early as one month of age and exhibit broadly adult-like patterns, though developmental differences persist (Levi et al., 1995).

Developmental factors influence reliability, particularly during infancy, where EFR amplitude and detectability vary with age and are more affected for low-frequency stimuli (Easwar et al., 2021; Nodarse et al., 2012). Methodological approaches can further impact response detection. For instance, combining multiple speech-evoked EFR measures has been shown to improve detection rates compared to single-stimulus recordings (Chesnaye et al., 2026).

2.2 Effects of hearing loss on Envelope Following Responses

Envelope Following Response characteristics are significantly altered in the presence of hearing loss, reflecting changes in neural encoding within the auditory pathway. Several studies have reported an overall reduction in EFR magnitude, particularly in individuals with high-frequency hearing loss, indicating degraded neural synchrony (Wartenberg et al., 2022).

Interestingly, despite this reduction, hearing impairment has been associated with enhanced neural encoding of the temporal envelope. Both physiological and human studies have demonstrated increased envelope tracking in hearing-impaired listeners, including evidence from auditory nerve fiber recordings following noise-induced hearing loss (Anderson et al., 2013). This enhancement appears consistent across age groups, with studies showing increased neural synchronization to envelope modulations in hearing-impaired adults compared to age-matched normal-hearing controls (Goossens et al., 2019).

However, this apparent enhancement of envelope coding is accompanied by a degradation in the representation of temporal fine structure, which plays a crucial role in complex listening environments. This imbalance between envelope and fine structure processing may contribute to the persistent difficulties in speech perception, particularly in noise, experienced by individuals with hearing loss despite amplification (Ananthakrishnan et al., 2016; Anderson et al., 2013).

2.2.1 Effects of hearing aid amplification on envelope following responses in adults

Envelope Following Response measures are significantly influenced by hearing aid amplification in adults with hearing loss, reflecting improvements in neural encoding of the speech envelope. The most consistent finding across studies is an increase in EFR amplitude with amplification. (Easwar et al. (2015), in adults with mild-to-moderately severe sensorineural hearing loss, demonstrated that aided conditions resulted in significantly greater response amplitudes and increased detection of EFRs across multiple speech frequency regions compared to unaided conditions. This suggests that amplification enhances neural representation of previously inaudible or weak acoustic cues.

In addition to amplitude changes, amplification has been shown to improve neural synchrony. Jenkins et al. (2018) reported enhanced phase locking and increased response amplitudes in older adults using hearing aids, with the greatest improvements observed in speech regions with reduced audibility, such as consonant transitions. These findings indicate that the benefits of amplification are both frequency-specific and level-dependent, with greater neural gains occurring in regions most affected by hearing loss.

Temporal aspects of neural processing also appear to improve with amplification. Reductions in response latency have been observed at both subcortical and cortical levels, suggesting more efficient neural encoding of amplified speech signals (Jenkins et al., 2018). Furthermore, studies examining aided bandwidth have shown that increasing the audible frequency range leads to improvements in both EFR amplitude and detection rates, reinforcing the importance of adequate bandwidth in hearing aid fittings (Easwar et al., 2015).

Importantly, EFR measures have demonstrated associations with behavioral outcomes, including speech perception and sound quality ratings, supporting their potential as objective indicators of hearing aid benefit (Easwar et al., 2015). While similar effects are not consistently observed in cortical responses, this suggests that subcortical measures such as EFRs may be more sensitive to changes in audibility introduced by amplification(Billings et al., 2007).

Despite these promising findings, the existing evidence base remains limited, with relatively small sample sizes and a focus on short-term amplification effects. Most studies have examined immediate responses following hearing aid fitting, with limited data on long-term neural adaptation. Overall, current evidence indicates that hearing aid amplification enhances EFR characteristics through increased amplitude, improved phase locking, and better detectability, particularly in frequency regions with reduced audibility. However, further research is required to establish their clinical utility as robust objective measures of hearing aid benefit.

Hearing aid amplification has been shown to enhance Envelope Following Response detection and response amplitude under aided conditions compared to unaided listening in adults with hearing loss. Easwar et al. (2015) reported that amplification significantly increased both the number of detectable EFRs and response amplitudes across multiple stimulus conditions, indicating improved neural representation of speech envelope cues. These enhancements were observed at different presentation levels, with consistent increases in response amplitude for the majority of stimulus carriers.

In addition, expanding the aided audible bandwidth was associated with further improvements in EFR detection and combined response amplitude, highlighting the importance of adequate frequency representation in hearing aid fittings. Notably, EFR measures demonstrated significant positive correlations with behavioral outcomes, including speech perception and sound quality ratings, supporting their validity as objective indicators of aided benefit. Overall, these findings suggest that aided EFRs are sensitive to changes in audibility and amplification, with responses influenced by both stimulus level and bandwidth characteristics.

Hearing aid amplification has been shown to enhance Envelope Following Response recordings primarily through improvements in audibility. Easwar et al. (2015) demonstrated that amplification significantly increased both EFR detection rates and response amplitudes in adults when comparing aided and unaided conditions across different presentation levels. These findings were further supported in pediatric populations, where improvements in EFR amplitude and detectability were found to depend on the extent of change in behavioral thresholds between unaided and aided conditions (Easwar et al., 2023). Notably, EFR detectability was strongly influenced by sensation level, with higher audibility associated with increased likelihood of response detection and improved sensitivity in aided conditions.

In addition to audibility, stimulus characteristics such as bandwidth have been shown to influence EFR outcomes. Increasing the audible bandwidth has been associated with improvements in both detection rates and overall response amplitude, highlighting the importance of adequate frequency representation in amplification (Easwar et al., 2015).

The effects of hearing loss–related changes in cochlear processing have also been explored using EFR measures. Encina-Llamas et al. (2020) examined EFR magnitude–level functions and reported reduced compressive behavior in hearing-impaired listeners, consistent with diminished basilar membrane compression. However, their findings also indicated that EFR responses are influenced by off-frequency neural contributions, limiting their ability to provide frequency-specific estimates of cochlear compression. Furthermore, the slope of EFR growth functions was found to be sensitive to both outer and inner hair cell dysfunction, suggesting that these measures reflect a combination of peripheral deficits rather than isolated compression mechanisms.

Despite evidence demonstrating clear effects of amplification on EFR characteristics, the influence of specific hearing aid processing parameters—such as compression ratio, release time, and channel configuration—remains largely unexplored. This represents an important gap in the literature, particularly in the context of understanding how hearing aid signal processing shapes neural encoding of speech.

Envelope Following Response measures have demonstrated a positive association with behavioral speech perception outcomes in aided individuals, supporting their potential as objective indicators of hearing aid benefit. In adults with mild-to-moderately severe hearing loss, Easwar et al. (2015) reported significant correlations between EFR parameters—such as detection rates and combined response amplitude—and speech discrimination scores under varying bandwidth conditions. Improvements in EFR detectability and amplitude with amplification closely paralleled enhancements in behavioral performance, suggesting that EFRs reflect changes in auditory processing relevant to functional listening.

Similar trends have been observed in pediatric populations, where aided improvements in EFR detectability were found to significantly predict changes in speech discrimination accuracy (Easwar et al., 2023). These findings further support the role of EFRs in capturing amplification-related benefits at a neural level.

However, the current evidence base remains limited to a small number of studies with relatively modest sample sizes. While the observed relationships appear robust in the context of audibility and bandwidth effects, further research involving larger and more diverse populations is necessary to establish the reliability and generalizability of EFR measures as predictors of hearing aid outcomes.

2.3 Envelope following responses with hearing aids in children

Envelope Following Response measures in children with Sensorineural Hearing Loss demonstrate clear improvements under aided conditions, reflecting enhanced neural encoding of speech-related acoustic cues. Easwar et al. (2023), in a study of children with mild-to-severe hearing loss, reported that hearing aid use significantly increased EFR detectability and response amplitude, with sensitivity improving from unaided to aided conditions alongside high specificity. Importantly, changes in EFR amplitude were found to correlate with improvements in behavioral thresholds and predict gains in speech discrimination, highlighting the relevance of these measures for assessing functional benefit.

Evidence from adult studies provides additional support for these findings, with amplification consistently shown to increase EFR amplitude and detection rates (Easwar et al., 2015). Improvements in neural responses with amplification have also been observed at cortical levels, suggesting that enhanced audibility facilitates more robust auditory processing across the pathway (Korczak et al., 2005; Billings et al., 2007).

Developmental factors further influence aided outcomes in children. Earlier provision of amplification has been associated with better auditory pathway functioning and improved long-term outcomes, emphasizing the importance of timely intervention (Chen et al., 2023; Sininger et al., 2010). Despite these benefits, some limitations persist. Even with appropriate amplification, deficits in temporal processing—particularly in fundamental frequency encoding under challenging listening conditions such as noise and reverberation—have been reported in children (Easwar et al., 2024).

Overall, current evidence indicates that hearing aid amplification enhances EFR characteristics in children and is associated with improvements in behavioral and speech outcomes. However, the available literature remains limited in scope, with relatively small sample sizes and a need for further research to better understand the extent to which EFR measures can reliably predict hearing aid benefit in pediatric populations.

Envelope Following Response measures in pediatric populations show clear improvements under aided conditions compared to unaided listening. Easwar et al. (2023), in children with mild-to-severe hearing loss, reported that hearing aid use significantly enhanced EFR amplitude and detectability, with the extent of improvement closely related to changes in behavioral thresholds. Notably, sensitivity of EFRs in predicting audibility was higher in aided conditions, while specificity for identifying inaudibility remained consistently high. Furthermore, improvements in EFR detectability were found to significantly predict changes in speech discrimination performance, indicating a strong link between neural encoding and functional auditory outcomes.

Envelope Following Response measures have demonstrated strong potential as objective indicators of aided audibility and hearing aid benefit in children. Studies have shown that aided conditions yield higher sensitivity compared to unaided listening, with improved EFR detectability and amplitude closely associated with gains in speech discrimination performance (Easwar et al., 2023). In school-aged children, EFR characteristics such as sensitivity and specificity have been found to approach adult-like levels, further supporting their reliability as measures of neural encoding (Easwar et al., 2022).

Despite these promising findings, the available evidence remains limited, with relatively few studies directly examining aided versus unaided EFRs in pediatric populations. This highlights the need for further research to validate the clinical utility of EFRs as objective measures of hearing aid benefit in children.

2.3.1 Influence of stimulus characteristics on aided EFR recordings in children

Envelope Following Response measures have demonstrated strong potential as objective indicators of aided audibility and hearing aid benefit in children. Studies have shown that aided conditions yield higher sensitivity compared to unaided listening, with improved EFR detectability and amplitude closely associated with gains in speech discrimination performance (Easwar et al., 2023). In school-aged children, EFR characteristics such as sensitivity and specificity have been found to approach adult-like levels, further supporting their reliability as measures of neural encoding (Easwar, Purcell, et al., 2022).

Frequency-specific patterns indicate that high-frequency stimuli are more reliably detected than low- and mid-frequency components, with lower sensation level requirements for fricative-based cues compared to low-frequency formants (Easwar et al., 2020). Developmental influences also play a role, with infants showing greater variability—particularly for low-frequency stimuli—and age-related changes in EFR characteristics during early life (Easwar et al., 2021). Despite improvements with amplification, children with hearing loss may continue to exhibit deficits in temporal processing, especially under complex listening conditions (Easwar et al., 2024).

Clinically, EFRs provide a valuable objective tool for assessing hearing aid benefit in pediatric populations who are unable to reliably participate in behavioral testing. Enhanced detectability of EFRs has been shown to predict speech discrimination outcomes, and the use of multi-stimulus paradigms may further improve sensitivity across frequency regions (Chesnaye et al., 2026; Easwar et al., 2023).

Stimulus characteristics play a crucial role in shaping aided Envelope Following Response recordings in children, with factors such as stimulus level, frequency content, and audibility interacting to influence response strength and detectability. Evidence suggests that sensation level, rather than absolute stimulus intensity, is a key determinant of EFR outcomes. Easwar et al. (2023) demonstrated that improvements in EFR amplitude and detectability with hearing aid use were closely related to changes in behavioral thresholds, with higher sensation levels resulting in increased likelihood of response detection. Similarly, Easwar, Aiken, et al. (2022) reported that EFR sensitivity and specificity in children remained high across a range of stimulus levels when audibility was taken into account, further emphasizing the importance of individualized stimulus calibration.

Stimulus frequency also significantly influences aided EFR characteristics. High-frequency components, particularly fricatives, tend to show greater detectability compared to low- and mid-frequency stimuli, although they may exhibit greater variability with age. In contrast, responses to low- and mid-frequency vowel components appear more stable across developmental stages (Easwar, Aiken, et al., 2022). The use of complex speech stimuli allows simultaneous assessment across multiple frequency regions, with aided conditions showing improved detectability across these components (Easwar et al., 2023).

Hearing aid amplification further modifies the relationship between stimulus characteristics and neural responses, with aided conditions consistently demonstrating higher sensitivity in predicting audibility compared to unaided listening. Improvements in EFR detectability have also been shown to predict changes in speech discrimination performance, indicating a meaningful link between neural encoding and functional auditory outcomes (Easwar et al., 2023).

Developmental factors must also be considered, as age-related changes in EFR characteristics vary across stimulus frequencies, particularly during early life when low-frequency responses show greater variability (Easwar et al., 2021). Overall, these findings highlight the importance of optimizing stimulus parameters—particularly sensation level and frequency content—when recording aided EFRs in children, while also indicating that further research is needed to refine stimulus protocols for clinical application.

2.3.2 Methodological challenges in recording aided EFRs in children

Although Envelope Following Response recordings have been successfully obtained in pediatric populations under aided conditions, the literature provides limited direct discussion of the specific challenges associated with such recordings. Existing studies demonstrate the feasibility of recording aided EFRs in children with hearing loss, but methodological constraints are often not explicitly detailed (Easwar et al., 2023; Easwar, Purcell, et al., 2022).

However, broader evidence from pediatric electrophysiological research suggests several practical and technical challenges that are likely relevant to aided EFR recording. Recording neural responses in children is inherently complex due to factors such as limited attention span, increased movement artifacts, and difficulties in maintaining stable electrode placement. High attrition rates are commonly reported, largely due to poor data quality or participant non-compliance, and recording sessions must often be completed within short time frames to maintain cooperation (Hoehl & Wahl, 2012).

These challenges may be further compounded in aided conditions, where the presence of hearing aids introduces additional considerations, including ensuring appropriate device functioning, maintaining consistent stimulus delivery, and minimizing potential sources of acoustic or electrical interference. Furthermore, age-related factors influence recording feasibility, with younger children presenting greater variability in response stability compared to older pediatric populations.

Overall, while aided EFR recordings are feasible in children, methodological challenges related to participant behavior, recording conditions, and device-related factors must be carefully managed. The limited explicit discussion of these challenges in current literature highlights the need for further research focusing on optimizing recording protocols for clinical application in pediatric populations.

2.4 Envelope following responses in cochlear implant users

The application of Envelope Following Response in children with Cochlear Implant remains relatively underexplored in the current literature. Existing research on EFRs in pediatric populations has primarily focused on typically developing children and those using hearing aids, where these measures have been established as reliable indicators of temporal envelope encoding and auditory processing (Easwar, Aiken, et al., 2022; Easwar et al., 2024;

Purcell et al., 2004b). However, comparable evidence examining EFRs in cochlear implant users is limited.

In contrast, studies involving children with cochlear implants have predominantly utilized other electrophysiological measures, such as mismatch negativity (MMN) and P3 components, to evaluate auditory discrimination and predict language outcomes. These measures have been shown to differentiate performance levels and provide insights into cortical auditory processing in implanted children (Singh et al., 2004; Deroche et al., 2023).

The limited application of EFRs in this population represents a gap in the literature, particularly given their potential to provide objective insights into subcortical temporal processing. Further investigation is therefore required to determine the utility of EFRs in assessing auditory function in children with cochlear implants.

2.4.1 Comparison of electrophysiological responses between cochlear implant and hearing aid users

Direct comparisons of Envelope Following Response between users of Cochlear Implant and hearing aids remain limited in the current literature. Existing studies have primarily examined EFR characteristics within specific populations rather than across device groups. In hearing aid users, speech-evoked EFRs have consistently shown increases in amplitude and detectability with amplification, along with improved sensitivity under aided conditions (Easwar et al., 2015, 2023).

Related electrophysiological measures provide indirect insights into differences in auditory processing across device users. For instance, frequency following responses recorded in bimodal listeners have been associated with perceptual benefits, suggesting contributions from residual acoustic hearing (Kessler et al., 2020). Similarly, cortical evoked response studies have demonstrated improved speech unmasking in cochlear implant users with preserved acoustic hearing compared to electric-only stimulation (Shim et al., 2023).

However, direct comparisons of EFR responses between cochlear implant and hearing aid users are lacking. This represents an important gap, as such comparisons could provide valuable insights into differences in neural encoding associated with acoustic and electric hearing.

Envelope Following Response (including electrically evoked steady-state responses) can be used to objectively assess how well the auditory pathway of Cochlear Implant users encodes temporal envelope modulations (TEMs), which are essential for speech perception. Evidence from electrically evoked paradigms indicates strong associations between neural responses and perceptual outcomes. Gransier, Luke, et al. (2020) reported a robust correlation between variability in 40-Hz responses across the electrode array and speech-in-noise performance, suggesting that neural encoding at specific electrodes is functionally meaningful. Subsequent work demonstrated that 40-Hz electrically evoked responses can be recorded during continuous stimulation with effective artifact control, supporting their clinical feasibility (Gransier, Carlyon, et al., 2020).

These findings indicate that EFR-based measures may help identify electrodes with suboptimal neural responses and inform device programming. However, the current evidence is derived from relatively small samples, and further studies are required to establish the reliability and generalizability of these measures in broader cochlear implant populations.

2.5 Relationship between EFR measures and behavioral outcomes

Envelope Following Response measures have demonstrated consistent and clinically meaningful relationships with behavioral auditory outcomes across different populations and stimulus conditions. In children with hearing loss, improvements in EFR amplitude under aided conditions have been shown to correlate with changes in behavioral thresholds, indicating that neural response enhancement reflects gains in audibility (Easwar et al., 2023). Notably, aided EFR detectability has been identified as a significant predictor of improvements in speech discrimination performance, supporting the use of EFRs as objective prognostic indicators of hearing aid benefit.

The strength of this relationship appears to depend on stimulus characteristics. High-frequency stimuli, particularly fricatives, have been shown to yield higher sensitivity in detecting audibility compared to low- and mid-frequency vowel components. In addition, sensitivity improves with increasing stimulus level, suggesting that both frequency content and presentation level influence the accuracy of EFR-based predictions (Easwar et al., 2020).

Evidence from adult populations further supports these findings, with significant positive correlations reported between EFR parameters and speech discrimination outcomes in individuals with hearing loss (Easwar et al., 2015). Similar patterns of sensitivity and specificity have also been observed across children and adults, indicating that EFR measures provide reliable indicators of auditory processing across age groups (Easwar, Aiken, et al., 2022).

From a clinical perspective, EFRs have shown sensitivity to changes in aided bandwidth that parallel improvements in behavioral speech perception, demonstrating convergent validity for use in hearing aid fitting and verification (Easwar et al., 2015). Collectively, these findings highlight the potential of EFRs as objective tools for assessing auditory performance and predicting hearing aid benefit. However, the variability introduced by stimulus parameters and the relatively limited number of studies underscore the need for further research to strengthen their clinical applicability.

2.5.1 EFRs and functional listening outcomes in children

Envelope Following Response measures have shown promise in predicting functional listening performance in children with hearing loss, particularly in complex listening environments. Neural encoding of low-frequency envelope cues has been found to significantly predict speech discrimination accuracy in noise and reverberation, indicating that EFRs capture aspects of auditory processing that are directly relevant to real-world communication (Easwar et al., 2024). These findings extend beyond basic audibility measures, highlighting the role of EFRs in reflecting higher-level listening demands.

Consistent with this, improvements in EFR detectability under aided conditions have been associated with corresponding gains in speech discrimination performance, further supporting their relevance for assessing functional auditory outcomes (Easwar et al., 2023). Together, these findings suggest that EFRs provide an objective index of how effectively amplified speech is processed under challenging conditions.

However, while evidence supports the relationship between EFRs and speech perception, their association with broader language development outcomes remains insufficiently explored. Current literature lacks direct investigations linking EFR measures with standardized language metrics such as vocabulary, syntax, or expressive and receptive language abilities. This represents an important gap, particularly given the central role of language development in pediatric hearing rehabilitation.

2.6 EFRs as predictors of hearing aid benefit in children

Envelope Following Response measures have shown emerging potential as objective predictors of hearing aid benefit in pediatric populations. Evidence from children with hearing loss indicates that improvements in EFR detectability under aided conditions are significantly associated with gains in speech discrimination performance, suggesting that neural response changes can reflect functional benefits of amplification (Easwar et al., 2023).

Supporting evidence from related neural measures further strengthens this perspective. Neural envelope tracking, which reflects similar underlying auditory processing mechanisms, has been shown to correlate strongly with speech intelligibility and to improve with hearing aid use in children, indicating sensitivity to amplification-related changes in auditory perception (Hirtum et al., 2023).

Foundational studies in typically developing children have also demonstrated that EFR measures exhibit high sensitivity and specificity and approach adult-like characteristics by school age, supporting their reliability as objective indicators of auditory encoding (Easwar, Aiken, et al., 2022).

Despite these promising findings, the current pediatric evidence base remains limited, with relatively small sample sizes and a need for further validation. Additional research is required to establish the robustness and clinical applicability of EFRs as predictive tools for hearing aid out.

2.6.1 Comparison of speech-evoked and frequency-specific EFRs in predicting hearing aid benefit

Envelope Following Response studies have not directly compared speech-evoked and frequency-specific approaches as predictors of hearing aid benefit in pediatric populations. However, available evidence provides indirect insights into their relative utility. Approaches that incorporate multiple frequency components appear to enhance response detectability. For instance, combining responses across several frequency bands has been shown to improve detection rates compared to analyzing individual frequency-specific components, suggesting that broader spectral representation may yield more robust neural measures (Chesnaye et al., 2026).

In the context of hearing aid benefit, speech-evoked EFR paradigms have demonstrated strong predictive value. Using complex speech stimuli, significant improvements in detectability under aided conditions have been shown to predict corresponding gains in speech discrimination performance, with high sensitivity and specificity reported in pediatric populations (Easwar et al., 2023). These findings indicate that speech-based stimuli, which inherently integrate multiple frequency regions, may provide functionally relevant information for assessing auditory benefit.

Despite these observations, direct comparisons between speech-evoked and frequency-specific EFR measures remain lacking. This limits the ability to determine which approach offers superior predictive accuracy for hearing aid outcomes. Further research is therefore required to systematically evaluate the relative effectiveness of these stimulus paradigms in pediatric populations.

2.7 Limitations of existing EFR research in pediatric populations

Envelope Following Response research in children remains limited by relatively small sample sizes and preliminary stages of validation. Current evidence on the use of EFRs for predicting hearing aid benefit is based on a small number of studies involving modest cohorts. For instance, investigations in children with hearing loss and in typically developing pediatric populations have included limited sample sizes, restricting the generalizability of findings (Easwar, Aiken, et al., 2022; Easwar et al., 2023).

Much of the foundational work in this area has also been derived from adult populations, serving as a basis for subsequent pediatric research (Easwar et al., 2015). While recent studies have demonstrated promising relationships between aided EFR improvements and speech discrimination outcomes, the restricted sample characteristics and limited diversity of participants highlight the need for broader validation.

Overall, the existing literature indicates that although EFRs show potential as objective measures in pediatric audiology, further research involving larger and more diverse populations is required to establish their reliability and clinical applicability.

2.7.1 Combined use of frequency-specific and speech-evoked EFR measures

Envelope Following Response research in pediatric populations has largely examined frequency-specific and speech-evoked responses independently, with limited studies integrating both approaches within the same framework. Earlier investigations in children have primarily focused on frequency-specific components of speech stimuli, analyzing responses to individual formants and fricative elements separately (Easwar, Aiken, et al., 2022; Easwar et al., 2021). While these studies provide valuable insights into frequency-dependent neural encoding, they do not evaluate the combined contribution of multiple stimulus types.

More recent work has begun to address this limitation. Chesnaye et al. (2026) examined both frequency-specific and non-frequency-specific EFR measures within the same experimental paradigm and demonstrated that combining these responses improved sensitivity for detecting audibility. This finding suggests that integrating multiple stimulus representations may provide a more comprehensive assessment of auditory processing in pediatric populations.

Despite this emerging evidence, studies combining frequency-specific and speech-evoked EFR measures remain scarce. Further research is therefore required to determine whether such combined approaches offer improved predictive accuracy for hearing aid benefit in children.

2.7.2. Lack of hybrid approaches combining tonal and speech-evoked EFRs

Envelope Following Response research in pediatric hearing aid users has predominantly focused on speech-evoked responses, with limited investigation into combined or hybrid stimulus approaches. Speech-evoked EFRs have demonstrated strong potential in predicting hearing aid benefit, with improvements in detectability and amplitude under aided conditions associated with gains in speech discrimination performance (Easwar et al., 2023). Similar findings in adult populations further support their sensitivity to changes in audibility, stimulus level, and bandwidth, reinforcing their clinical relevance as objective outcome measures (Easwar et al., 2015).

However, existing studies have largely evaluated speech-based EFRs in isolation, without systematically examining the potential advantages of integrating tonal (frequency-specific) and speech-evoked stimuli within the same assessment framework. Given that tonal EFRs provide precise frequency-specific information while speech-evoked EFRs capture more complex, ecologically valid processing, a combined approach may offer complementary insights into auditory function.

The absence of studies investigating such hybrid paradigms represents a critical gap in the literature. Further research is therefore required to determine whether combining tonal and speech-evoked EFR measures can improve the prediction of hearing aid benefit in pediatric populations.

Summary and research gap

The existing body of literature demonstrates that Envelope Following Response measures provide valuable insights into neural encoding of temporal envelope cues and show promising potential as objective indicators of hearing aid benefit in pediatric populations. Evidence suggests that EFR characteristics are influenced by stimulus parameters, developmental factors, and audibility, and are associated with behavioral outcomes such as speech perception and functional listening. Studies in both adults and children have highlighted improvements in EFR amplitude and detectability under aided conditions, along with emerging evidence supporting their role in predicting hearing aid–related gains.

However, several limitations remain. The current pediatric evidence base is limited in scope, with relatively small sample sizes and a lack of large-scale validation. Direct comparisons between different stimulus paradigms—particularly speech-evoked and frequency-specific EFRs—are scarce, and the potential advantages of combining these approaches have not been systematically explored. Furthermore, methodological challenges in recording aided EFRs in children and the limited application of these measures in special populations, such as cochlear implant users, highlight gaps in current understanding.

In particular, there is a lack of studies investigating the combined use of frequency-specific and speech-evoked EFR measures as predictors of hearing aid benefit in children with sensorineural hearing loss. Given that these stimulus types provide complementary information regarding auditory processing, integrating them may enhance the accuracy and clinical utility of EFR-based assessments.

Therefore, the present study aims to evaluate aided envelope following responses to both frequency-specific and speech stimuli and to examine their potential as predictors of hearing aid benefit in children with sensorineural hearing loss.

CHAPTER III

Methods

3.1 Study Design

The present study employed a **correlational, non-experimental research design**, wherein the relationships between electrophysiological and behavioral measures were examined without manipulation of variables. Specifically, the study aimed to investigate the association between aided Envelope Following Response measures (obtained using frequency-specific tonal and speech stimuli) and behavioral measures, including aided audiometric thresholds, speech perception, and language development, in children with sensorineural hearing loss.

Participants were selected using a **convenience sampling method**, wherein children who met the inclusion criteria and were available during the study period were recruited. Participants were further categorized into groups based on the degree of hearing loss (moderate to moderately severe and severe to profound) to facilitate comparative analysis.

3.2 Participants

The study comprised children aged 3-5 years with bilateral congenital sensorineural hearing loss using hearing aids. A total of 26 participants (13 in each group) were included who were categorized into two groups based on the degree of hearing loss: (i) moderate to moderately severe hearing loss group (pure tone average ≤70 dB HL) and (ii) severe to profound hearing loss group (pure tone average >70 dB HL).

All participants had a documented history of at least two months of hearing aid use and were undergoing consistent speech-language and listening therapy.

Children were excluded if they had active conductive hearing loss at the time of testing, history of recurrent middle ear pathology, evidence of retrocochlear pathology, below-average intellectual ability, or any additional developmental disabilities.

Prior to participation, the study procedures were explained in detail to the parents, and written informed consent was obtained.

3.2.1 Sample size estimation

The sample size for the present study was estimated with reference to previous studies examining aided Envelope Following Response measures in children with hearing loss (Easwar, Aiken, et al., 2022; Easwar et al., 2023). Based on the findings reported in these studies, a moderate effect size (d = 0.35) was considered appropriate for the current investigation. Using a significance level (alpha) of 0.05 and a statistical power of 80%, the required sample size was estimated.

Taking into account participant availability, feasibility of pediatric electrophysiological recordings, and the duration of the study, a total of 20 children with sensorineural hearing loss were included. The participants were further grouped according to the degree of hearing loss for subsequent analysis.

3.3 Procedure

All assessments were carried out in a sound-treated, electrically shielded room under controlled conditions. Behavioral and electrophysiological tests were conducted monaurally in the better ear, with the right ear selected in cases where both ears showed similar hearing sensitivity.

The child was seated comfortably either on a caregiver's lap or in a chair, positioned at 0° azimuth relative to the loudspeaker. To facilitate cooperation and minimize movement artifacts, silent age-appropriate videos with subtitles were presented during the testing.

3.3.1 Aided Audiogram

Aided audiometric evaluation was carried out using a calibrated two-channel audiometer in a free-field setup. Warble tones were presented through loudspeakers positioned at 0° azimuth. Aided thresholds were obtained across frequencies ranging from 250 Hz to 8 kHz using the modified Hughson–Westlake procedure.

Care was taken to ensure that the child remained attentive and responded consistently to the stimuli. Detection of Ling six sounds was also assessed under aided conditions to obtain a functional estimate of audibility across low-, mid-, and high-frequency speech regions.

3.3.2 Language Evaluation

Receptive and expressive language abilities were evaluated using The Assessment Checklist for Speech-Language Skills (ACSLS). The assessment was conducted in a quiet and child-friendly environment to facilitate optimal participation.

The test evaluated various domains of early communication, providing an estimate of the child's language development relative to age expectations. Care was taken to ensure that the child was comfortable and engaged throughout the assessment to obtain valid responses.

3.3.3 Envelope Following Responses (EFR)

Envelope Following Response recordings were carried out in a sound-treated and electrically shielded room to minimize environmental and electrical interference. The child was seated comfortably either on a caregiver's lap or in a chair, facing the loudspeaker positioned at 0° azimuth. To ensure a relaxed and cooperative state throughout the recording, silent age-appropriate videos with subtitles were presented.

EFRs were recorded under **aided conditions** to evaluate neural encoding of amplified auditory signals. Both **frequency-specific amplitude-modulated tonal stimuli** and **speech-like stimuli** were employed. The use of frequency-specific stimuli allowed assessment of neural encoding across individual frequency regions, while speech stimuli provided insight into the processing of more complex and functionally relevant signals. This combined approach has been shown to be effective in evaluating aided audibility and speech-related outcomes (Easwar et al., 2015, 2020, 2023).

Recordings were obtained monaurally from the better ear. A vertical electrode montage was used, with the non-inverting electrode placed at the vertex (Cz), the inverting electrode at the nape of the neck, and the ground electrode at the mastoid. Electrode impedance was maintained below 3 kΩ to ensure good signal quality.

Stimuli were delivered through a calibrated loudspeaker, and responses were recorded using appropriate amplification and band-pass filtering settings. Artifact rejection criteria were applied to minimize contamination from movement and electrical noise, which is particularly important in pediatric recordings. Each recording lasted approximately 7-8 minutes, and short breaks were provided when required to maintain the child's comfort and cooperation.

EFRs reflect phase-locked neural activity to the temporal envelope of acoustic stimuli, primarily originating from subcortical auditory structures. Due to their relative independence from attention and sleep state, they are well suited for use in young children (Easwar et al., 2023). Their sensitivity to changes in audibility and amplification further supports their application in evaluating hearing aid benefit (Easwar et al., 2015, 2023).

The recorded signals were analyzed using Fourier-based spectral analysis. The presence of an EFR was determined by comparing the amplitude at the target modulation frequency with the surrounding noise floor. A response was considered present when the amplitude exceeded the noise level, and corresponding amplitude values were obtained for further analysis.

3.4 Stimulus

Envelope Following Response recordings were elicited using both **frequency-specific amplitude-modulated (AM) tonal stimuli** and **speech stimuli** under aided listening conditions. The use of these two stimulus types enabled assessment of neural encoding across discrete frequency regions as well as processing of complex, ecologically relevant speech signals. Such combined stimulus paradigms have been shown to provide comprehensive information regarding auditory encoding and aided audibility (Easwar et al., 2015, 2020, 2023).

Tonal and Speech-like stimuli were generated to elicit envelope following responses (EFRs) across multiple frequency regions simultaneously (Figures 1 & 2). The stimuli were generated at a sampling rate of 44.1 kHz using custom written code in MATLAB software.

AM Tone Complex: The first stimulus consisted of four sinusoidal carriers at 500, 1000, 2000, and 4000 Hz, each amplitude-modulated at a unique frequency to enable frequency-specific tagging of neural responses. Modulation frequencies were 80 Hz (500 Hz carrier), 88 Hz (1 kHz carrier), 96 Hz (2 kHz carrier), and 104 Hz (4 kHz carrier), with 100% modulation depth applied to all carriers. The four AM tones were summed with equal amplitude weighting to create an 800 ms stimulus complex.

Speech-Envelope NBN Stimulus: The second stimulus was designed to approximate speech-like temporal characteristics while retaining frequency-specific EFR tags. Four narrowband noise (NBN) carriers were generated with center frequencies of 500, 1000, 2000, and 4000 Hz and bandwidths of 80, 100, 200, and 400 Hz, respectively. Each NBN carrier was amplitude-modulated at the same tag frequencies as the tonal stimulus (80, 88, 96, and 104 Hz) with 100% modulation depth. The combined signal was then shaped by a spondaic speech envelope with equal stress on both syllables, implemented using raised-cosine onset/offset ramps (60 ms rise/fall time) and a 50% amplitude floor between syllables to minimize spectral splatter in the modulation domain. Total stimulus duration was 800 ms.

Figure 3.1. *AM tone complex stimulus. Top row: combined waveform (left), first 50 ms showing complex beating pattern (center), and spectrogram showing the four carrier frequencies at 500, 1000, 2000, and 4000 Hz (right). Bottom row: individual AM tones with their respective modulation frequencies (left), power spectrum with carrier frequency peaks (center), and envelope spectrum showing discrete peaks at the EFR tag frequencies of 80, 88, 96, and 104 Hz (right).*

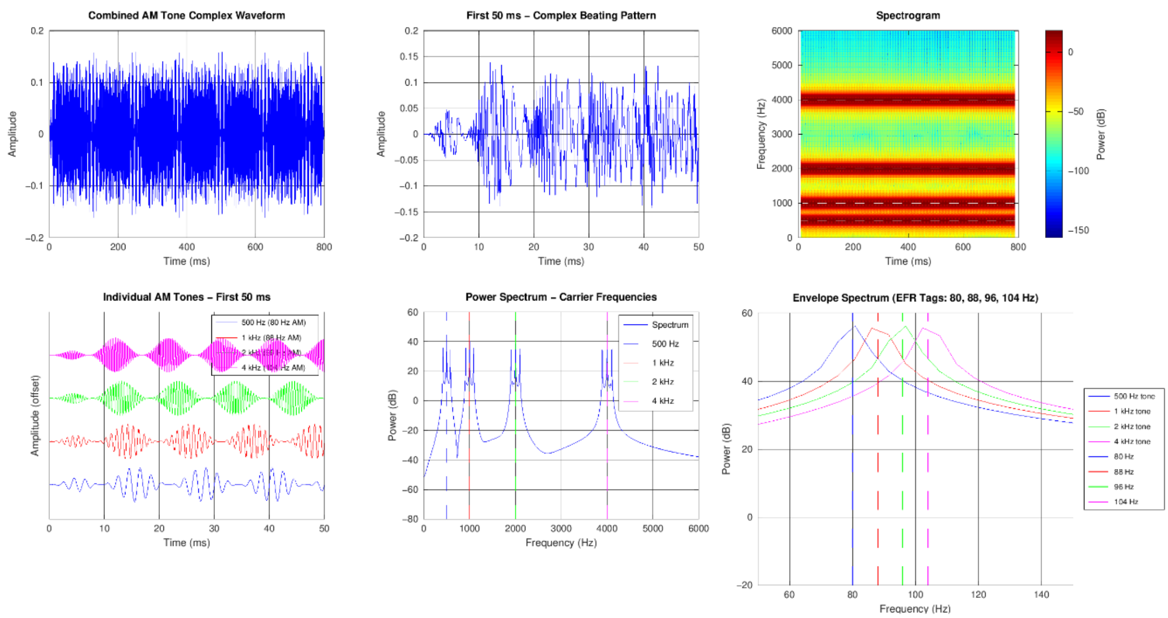
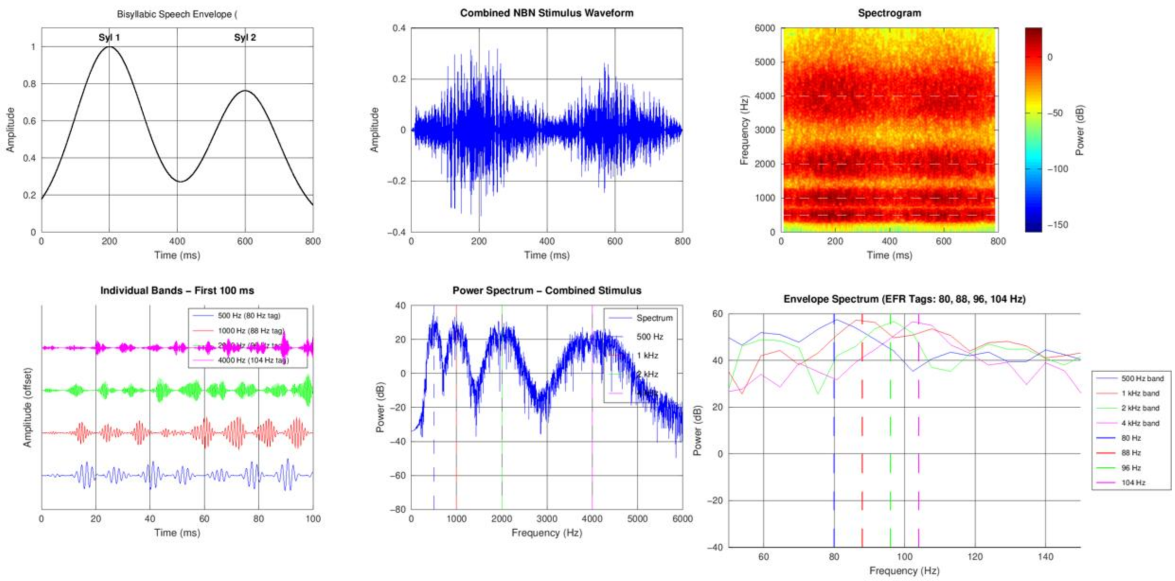


Figure 3.2. *Speech-envelope narrowband noise (NBN) stimulus. Top row: bisyllabic (spondaic) speech envelope with equal stress on both syllables (left), combined NBN stimulus waveform (center), and spectrogram showing the four NBN carrier bands (right). Bottom row: individual NBN bands with frequency-specific AM tags during the first 100 ms (left), power spectrum of the combined stimulus (center), and envelope spectrum showing peaks at the EFR tag frequencies of 80, 88, 96, and 104 Hz superimposed on the broader speech envelope modulation (right).*



3.4.1 Frequency-Specific Amplitude-Modulated Tonal Stimuli

Frequency-specific EFRs were obtained using **sinusoidally amplitude-modulated pure tones**. Carrier frequencies of **500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz** were selected to represent low-, mid-, and high-frequency regions of the speech spectrum. These frequencies were chosen to correspond to clinically relevant regions for speech perception.

Each carrier signal was modulated at a unique modulation frequency to allow independent identification of responses across frequency channels during spectral analysis. The modulation frequencies were assigned as follows:

500 Hz carrier → 80 Hz modulation frequency

1000 Hz carrier → 88 Hz modulation frequency

2000 Hz carrier → 96 Hz modulation frequency

4000 Hz carrier → 104 Hz modulation frequency

All tonal stimuli were presented with a modulation depth of 100%, ensuring maximal envelope contrast and robust neural phase-locking. The use of distinct modulation frequencies for each carrier allowed separation of responses in the frequency domain, enabling simultaneous or sequential evaluation of frequency-specific neural encoding (Easwar et al., 2023).

Stimuli were generated and presented in a manner that ensured adequate audibility under aided conditions, allowing assessment of neural encoding across the audible frequency range.

3.4.2 Speech Stimuli

Speech-evoked EFRs were obtained using a **complex speech token** comprising multiple phonemic components representing different spectral regions of speech. The stimulus included both **vowel formants (low- and mid-frequency components)** and **fricative elements (high-frequency components)**, thereby enabling simultaneous assessment of neural encoding across the speech spectrum.

To facilitate frequency-specific analysis within the speech signal, individual spectral components of the stimulus were amplitude-modulated using the same set of modulation frequencies as the tonal stimuli (**80 Hz, 88 Hz, 96 Hz, and 104 Hz**). Each modulation frequency corresponded to a specific frequency region of the speech signal, allowing extraction of multiple frequency-specific responses from a single complex stimulus.

The modulation depth was maintained at **100%**, ensuring strong temporal envelope cues and improved detectability of responses. This approach allowed efficient recording of speech-evoked EFRs while preserving ecological validity, as speech stimuli more closely represent real-world listening conditions compared to tonal stimuli (Easwar et al., 2015, 2023).

3.4.3 Stimulus Presentation

All stimuli were delivered at 65 dB SPL through a **calibrated loudspeaker** positioned at **0° azimuth** relative to the participant. Stimulus presentation was carried out under **aided conditions**, ensuring that all signals were processed through the participant's hearing aids.

Care was taken to maintain consistent stimulus levels and audibility across all conditions. The presentation parameters were selected to ensure optimal neural synchrony while maintaining participant comfort and cooperation.

The combination of frequency-specific tonal stimuli and speech stimuli provided a comprehensive assessment of auditory processing by capturing both **spectrally specific neural encoding** and **functional speech-related responses**. This dual approach enhances the ability to evaluate hearing aid benefit in pediatric populations.

Table 3.1. *Stimulation and Recording Parameters of Envelope Following Response*

Stimulus parameters	
Stimulus	Tone AM stimulus Speech-like stimulus
Stimulus Duration	800 ms
Polarity	Alternating
Presentation	Simultaneous
Intensity	65 dB SPL
Acquisition parameters	
Transducer	Calibrated Loudspeaker
Presentation	Sound field speakers (0° azimuth)
Ear	Monaural, better ear Right ear if both are similar
Repetition Rate	0.6/s
Analysis Window	900 ms (post)
Number of sweeps	750 sweeps Spectral Filter 60 – 130 Hz
Amplification	1,00,000
Artefact rejection	25 µV
Electrode Placement	Vertical montage Non-inverting (active): Vertex (Cz) Inverting (reference): Nape of neck Ground: Mastoid
Impedance	<3 kΩ
Total Recording Time	Around 30-40 minutes

Chapter IV

Results

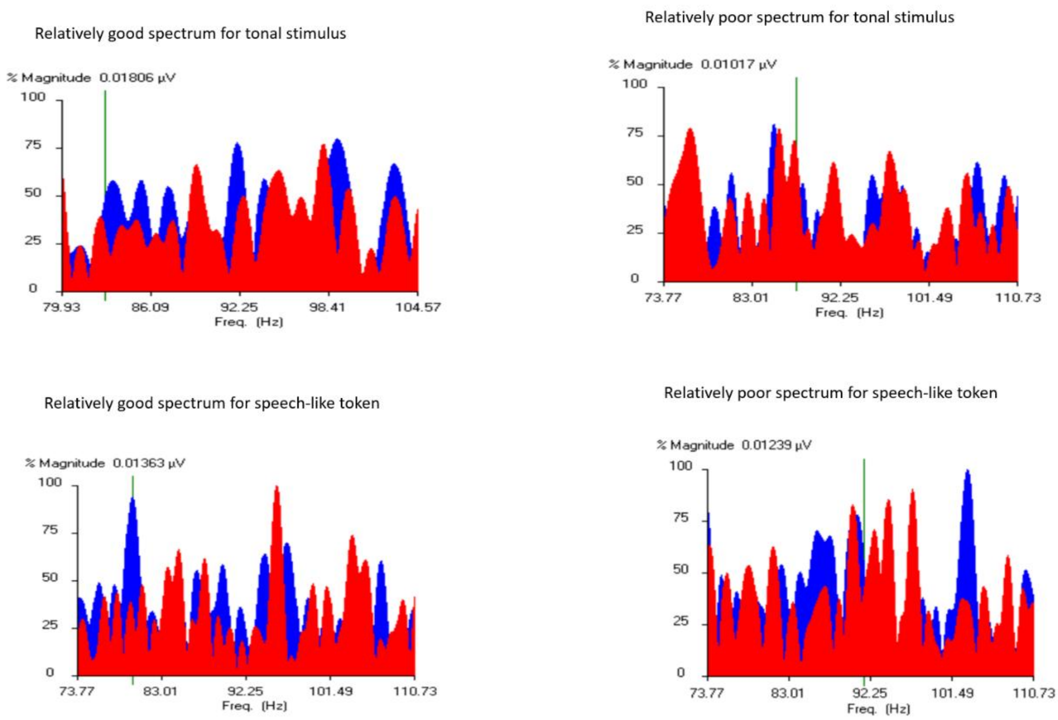
The present study examined the clinical utility of a hybrid envelope following response (EFR) protocol, combining frequency-specific amplitude-modulated (AM) tonal stimuli and ecologically valid speech stimuli, for the objective evaluation of hearing aid benefit in children with sensorineural hearing loss. Twenty-six children were analysed in two groups defined by degree of hearing loss: a moderate to moderately severe group (Group 1, n = 13) and a severe to profound group (Group 2, n = 13). The two groups were comparable in chronological age (Group 1: M = 45.5 months, SD = 10.8; Group 2: M = 48.2 months, SD = 8.4), although Group 2 had accrued more listening experience through hearing aid use (M = 20.6 months, SD = 8.5) than Group 1 (M = 11.2 months, SD = 7.1).

Prior to analysis, EFR amplitudes for both stimulus types were assessed for normality with Shapiro-Wilk test and it was found that most of the variables were found to be positively skewed ($p < 0.05$). Accordingly, all EFR amplitude values were subjected to a log10 transformation, which resulted in all the variables having a nearly normal distribution (Appendix 1), and satisfied the assumptions of the parametric analyses that follow. Relationships between log-transformed EFR amplitudes and behavioral measures were evaluated using Pearson product–moment correlations and simple linear regression, conducted separately for the two groups. The results are organised around the study's three objectives, with primary emphasis on the prediction of frequency-specific aided thresholds, which represents the principal clinical application of the protocol.

Representative EFR waveforms and their corresponding spectral analyses obtained using both AM and speech stimuli are presented first to illustrate the quality of recorded responses.

This is followed by analyses addressing each study objective, including the relationship between EFR amplitudes and aided behavioral thresholds and the predictive utility of the hybrid EFR protocol in children with sensorineural hearing loss.

Figure 4.1. *Representative good and poor Envelope Following Response (EFR) waveforms along with their corresponding spectral analyses for amplitude-modulated (AM) stimuli and speech stimuli.*



4.1 Descriptive Statistics

Descriptive statistics for the demographic, audiological, behavioral, and language measures are summarised in Table 4.1, and the corresponding EFR amplitudes (raw and log-transformed) in Table 4.2. As expected from the grouping criterion, aided thresholds were higher (poorer) in the severe-to-profound group across all frequencies, and this group also showed higher Ling-6 detection thresholds and somewhat higher variability in language age. EFR amplitudes were small (of the order of a few hundredths of a microvolt) in both groups, consistent with aided recordings in young children, and showed considerable inter-individual spread, particularly at the lower frequencies.

Table 4.1. *Descriptive statistics for demographic, behavioral, and language measures across the two participant groups.*

Variable	G1 Mean (SD)	G1 Range	G2 Mean (SD)	G2 Range
AGE	45.5 (10.8)	28–59	48.2 (8.4)	36–60
INTERV_AGE	33.8 (11.2)	12–53	27.5 (7.6)	14–40
LISTEN_AGE	11.2 (7.1)	4–24	20.6 (8.5)	5–40
A_500	31.5 (8.3)	15–40	43.8 (11.8)	25–60
A_1000	36.2 (8.7)	15–50	49.2 (13.0)	30–65
A_2000	41.2 (9.8)	20–55	58.1 (17.9)	35–90
A_4000	46.9 (12.7)	15–60	63.5 (19.8)	35–90
SDT	32.7 (10.5)	15–55	42.7 (10.1)	30–60
RLA_m	18.7 (9.9)	11–39	24.7 (13.7)	8–52
ELA_m	14.0 (7.8)	8–32	19.0 (10.9)	5–39
/a/	31.2 (6.8)	2045	39.2 (15.1)	20–65
/i/	33.5 (8.5)	20–45	43.8 (14.5)	25–65
/u/	35.0 (7.9)	20–45	44.6 (14.6)	25–70
/m/	36.5 (9.9)	20–50	49.2 (16.8)	25–85
/s/	42.3 (11.8)	20–55	54.6 (14.6)	35–80
/ʃ/	42.3 (11.5)	25–55	54.6 (15.3)	30–80

Note. G1 = moderate to moderately severe hearing loss group (n = 13); G2 = severe to profound hearing loss group (n = 13). All age values are in months. Aided thresholds (A_500, A_1000, A_2000, A_4000) and SDT are reported in dB HL. Ling-6 sound detection scores (/a/, /i/, /u/, /m/, /s/, /ʃ/) are aided detection thresholds in dB HL. RLA_m = receptive language age (median score); ELA_m = expressive language age (median score).

Table 4.2. *Descriptive statistics for Envelope Following Response (EFR) amplitudes at the nearest peak frequency, for AM tone and speech stimuli.*

Stimulus	**Freq (Hz)**	**G1 Raw M (µV) (SD)**	**G1 log M (SD)**	**G2 Raw M (µV) (SD)**	**G2 log M (SD)**
AM Tone	500	0.0069 (0.0044)	-2.28 (0.39)	0.0097 (0.0174)	-2.37 (0.54)
Speech		0.0074 (0.0058)	-2.38 (0.64)	0.0098 (0.0151)	-2.31 (0.52)
AM Tone	1000	0.0113 (0.0179)	-2.21 (0.46)	0.0116 (0.0220)	-2.32 (0.53)
Speech		0.0073 (0.0112)	-2.49 (0.65)	0.0105 (0.0144)	-2.34 (0.59)
AM Tone	2000	0.0058 (0.0032)	-2.33 (0.34)	0.0035 (0.0022)	-2.55 (0.32)
Speech		0.0066 (0.0047)	-2.41 (0.62)	0.0051 (0.0028)	-2.38 (0.32)
AM Tone	4000	0.0096 (0.0099)	-2.24 (0.48)	0.0033 (0.0017)	-2.53 (0.23)
Speech		0.0066 (0.0054)	-2.33 (0.41)	0.0037 (0.0028)	-2.56 (0.36)

Note. Raw EFR amplitude values are reported in microvolts (µV). Log values represent log_{10}-transformed amplitudes used in subsequent parametric analyses. G1 = moderate to moderately severe hearing loss group; G2 = severe to profound hearing loss group.

4.2 Prediction of Aided Thresholds from EFR Amplitude

The central clinical question of the study was whether aided EFR amplitude can serve as an objective predictor of frequency-specific aided thresholds. For each carrier frequency, the log-transformed EFR amplitude was entered as the predictor and the aided threshold at the corresponding frequency as the outcome in a simple linear regression. This frequency-matched approach was applied separately for AM-tone and speech EFRs, and separately for the two groups.

4.2.1 Moderate to Moderately Severe Group

In Group 1, EFR amplitude did not predict aided thresholds at any frequency, for either stimulus type. All models were non-significant and accounted for negligible variance (AM tone: R^2 = .002-.029, all $p > .57$; speech: R^2 = .001-.093, all $p > .31$). Consequently, the remaining threshold-prediction analyses were focused on the severe-to-profound hearing loss group (Table 3).

Table 4.3. *Pearson correlations between log-transformed EFR amplitudes and behavioral measures: Group 1 (Moderate to Moderately Severe HL, n = 13).*

Stimulus	Freq (Hz)	A_500	A_1000	A_2000	A_4000	SDT	RLA	ELA
AM Tone	500	0.11	-0.01	0.10	-0.10	0.36	-0.19	-0.12
Speech		0.17	-0.05	-0.00	-0.26	0.33	-0.34	-0.18
AM Tone	1000	-0.03	-0.17	-0.05	-0.04	0.11	-0.17	-0.06
Speech		-0.04	-0.21	-0.14	-0.28	0.14	-0.27	-0.12
AM Tone	2000	-0.08	-0.13	-0.04	-0.26	0.29	-0.35	-0.30
Speech		0.16	-0.05	-0.01	-0.27	0.37	-0.23	-0.08
AM Tone	4000	0.09	0.05	0.09	-0.12	0.56*	-0.12	-0.08
Speech		0.03	-0.09	-0.07	-0.30	0.30	-0.10	-0.02

Note. Cells display Pearson r values. A_500–A_4000 = aided thresholds (dB HL); SDT = speech detection threshold (dB HL); RLA = receptive language age (months); ELA = expressive language age (months). *p < .05, **p < .01.

Table 4.4. *Pearson correlations between log-transformed EFR amplitudes and behavioral measures: Group 2 (Severe to Profound HL, n = 13).*

Stimulus	Freq (Hz)	A_500	A_1000	A_2000	A_4000	SDT	RLA	ELA
AM Tone	500	-0.62*	-0.69**	-0.74**	-0.84**	-0.26	0.49	0.59*
Speech		-0.51	-0.59*	-0.67*	-0.70**	-0.13	0.32	0.42
AM Tone	1000	-0.41	-0.54	-0.56*	-0.67*	-0.08	0.43	0.53
Speech		-0.48	-0.61*	-0.68*	-0.77**	-0.04	0.46	0.56*
AM Tone	2000	-0.52	-0.58*	-0.57*	-0.54	-0.21	0.43	0.57*
Speech		-0.66*	-0.74**	-0.77**	-0.80**	-0.35	0.67*	0.76**
AM Tone	4000	-0.61*	-0.70**	-0.72**	-0.81**	-0.25	0.72**	0.72**
Speech		-0.50	-0.54	-0.53	-0.61*	-0.38	0.45	0.54

Note. Cells display Pearson r values. Negative correlations with aided thresholds indicate that higher EFR amplitudes are associated with better (lower) aided thresholds. Positive correlations with language measures indicate that higher EFR amplitudes are associated with higher language age scores. *p < .05, **p < .01.

4.2.2 Severe to Profound Group

In marked contrast, EFR amplitude was a robust predictor of aided thresholds throughout Group 2 (Table 4.4). Every frequency-matched model showed a negative slope, indicating that larger EFR amplitudes were associated with better (lower) aided thresholds- the direction expected if stronger neural encoding reflects greater aided audibility. The strongest single predictor was the 4000 Hz AM-tone EFR, which accounted for 66% of the variance in the 4000 Hz aided threshold ($R^2 = .658$, $F(1,11) = 21.20$, $p < .001$). The 2000 Hz speech EFR was the next strongest, explaining 60% of the variance in the 2000 Hz aided threshold ($R^2 = .597$, $F(1,11) = 16.31$, $p = .002$).

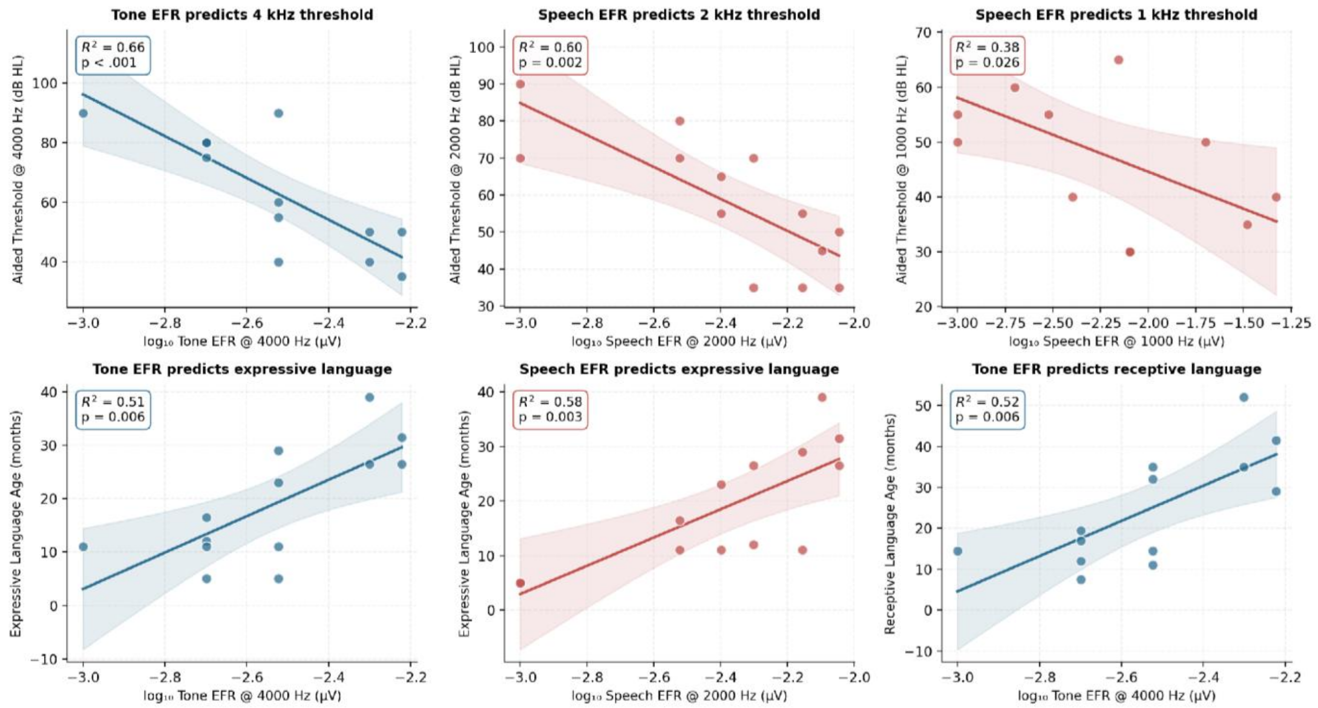
At the lower frequencies the relationships were more modest but still meaningful. The 500 Hz AM-tone EFR predicted the 500 Hz aided threshold ($R^2 = .383$, $p = .024$), and the 1000 Hz speech EFR predicted the 1000 Hz aided threshold ($R^2 = .376$, $p = .026$). The full regression coefficients, standard errors, and model statistics are reported in Table 4.5, and the bivariate relationships for the strongest models are displayed in Figure 1.

Table 4.5. *Frequency-matched simple linear regressions predicting aided thresholds from log-transformed EFR amplitudes in the Severe to Profound hearing loss group (n = 13).*

Stimulus	Freq (Hz)	β_0	β_1	SE(β_1)	R^2	Adj R^2	F	p
AM Tone	500	11.93	-13.46	5.15	0.383	0.327	6.83	0.024
Speech		17.44	-11.41	5.88	0.255	0.188	3.77	0.078
AM Tone	1000	18.45	-13.27	6.24	0.291	0.227	4.52	0.057
Speech		17.65	-13.47	5.23	0.376	0.319	6.63	0.026
AM Tone	2000	-22.96	-31.79	13.74	0.327	0.266	5.35	0.041
Speech		-44.62	-43.15	10.68	0.597	0.561	16.31	0.002
AM Tone	4000	-114.46	-70.23	15.25	0.658	0.627	21.20	<.001
Speech		-21.46	-33.16	13.14	0.367	0.309	6.37	0.028

Note. Model: $A\_freq = \beta_0 + \beta_1 \times \log_{10}$(EFR amplitude at corresponding carrier frequency). β_0 = intercept; β_1 = slope; SE(β_1) = standard error of the slope; F = model F-statistic; p = model p-value. Negative slopes indicate that higher EFR amplitudes predict lower (better) aided thresholds.

Figure 4.2.*EFR amplitude versus aided thresholds and language age, with fitted regression lines and 95% confidence bands — Severe-to-Profound HL group (n = 13). The upper row shows the frequency-matched prediction of aided thresholds; the negative slopes indicate that larger EFR amplitudes are associated with better aided thresholds.*



Taken together, these results indicate that in children with severe-to-profound hearing loss, the population in which objective verification of hearing aid benefit is most difficult to obtain behaviorally, the aided EFR provides a clinically useful, frequency-specific index of aided audibility, with the high-frequency responses being particularly informative.

4.3 EFR Correlations with Behavioral and Language Measures

Objectives 1 and 2 concerned the broader pattern of association between aided EFRs for tonal and speech stimuli respectively, and the behavioral measures of aided audibility and language development. Pearson correlations for the two groups are presented in Tables 4.3 and 4.4.

Consistent with the regression findings, the Moderate to Moderately Severe hearing loss group showed no systematic associations: correlations between EFR amplitude and any behavioral measure were uniformly weak and non-significant, with the single exception of one isolated coefficient consistent with chance at the .05 level. In the Severe to Profound hearing loss group, by contrast, a coherent pattern emerged. EFR amplitudes were positively correlated with both receptive and expressive language age, indicating that children with stronger neural encoding tended to have more advanced language. The speech detection threshold (SDT) did not correlate meaningfully with EFR amplitude in either group ($p > 0.05$).

A supplementary check confirmed that Ling-6 sound detection added little frequency-specific information beyond the aided audiogram: each Ling-6 sound correlated moderately-to-strongly with aided thresholds at every frequency rather than preferentially with its dominant spectral region, reflecting the highly intercorrelated audiometric configuration typical of severe-to-profound loss (Table 4.6). Ling-6 detection therefore largely indexes overall aided audibility, and its associations with EFR amplitude mirror those already described for the aided thresholds.

Table 4.6. *Pearson correlations between Ling-6 detection scores and aided thresholds in the Severe to Profound Hearing Loss group (n = 13).*

Ling Sound	A_500	A_1000	A_2000	A_4000
/a/	0.63	0.66	0.69	0.68
/i/	0.62	0.67	0.70	0.68
/u/	0.66	0.74	0.77	0.77
/m/	0.63	0.62	0.58	0.55
/s/	0.75	0.76	0.75	0.69
/ʃ/	0.73	0.76	0.73	0.72

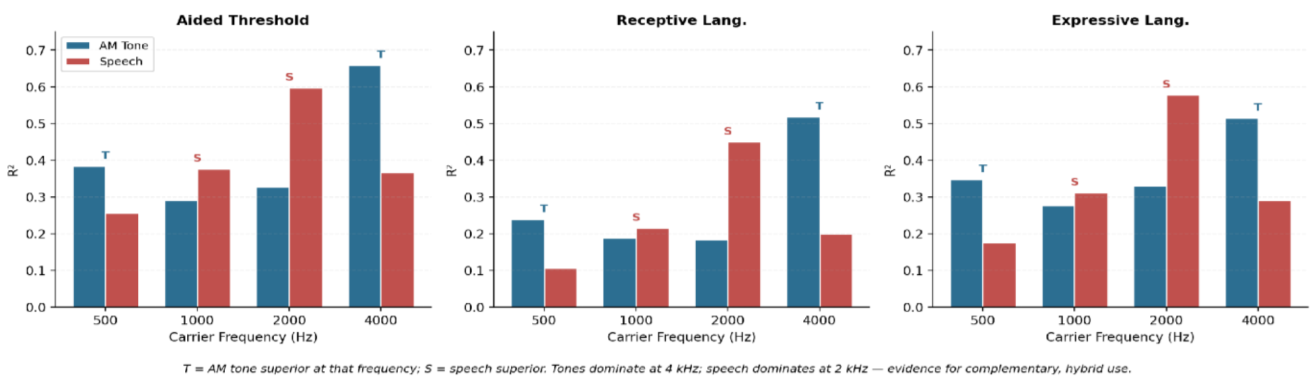
Note. Cells display Pearson r. All Ling-6 sounds correlate moderately-to-strongly with aided thresholds at every frequency, not preferentially with their dominant spectral region — reflecting the highly intercorrelated audiometric configuration typical of severe-to-profound loss. Ling-6 detection therefore largely indexes overall aided audibility rather than frequency-specific audibility. *$p < .05$, **$p < .01$.

4.4 Relative Predictive Value of Tonal and Speech EFRs

The third objective compared the predictive value of AM-tone and speech EFRs for the same outcomes at matched frequencies. Because the two EFR types were themselves highly correlated at each frequency (r = .63–.95), formal tests for the difference between dependent correlations (like Williams's t and Steiger's z) were statistically underpowered at the available sample size. The descriptive pattern of explained variance, however, was systematic and clinically informative.

As shown in Figure 4.3, the two stimulus types were *complementary*. AM tones were the stronger predictor at 4000 Hz, outperforming speech by up to 0.32 in R^2, whereas speech was the stronger predictor at 2000 Hz, outperforming tones by up to 0.27 in R^2. At 500 and 1000 Hz the two stimulus types performed comparably. This pattern is consistent with the acoustic properties of the stimuli: a clean tonal carrier provides a more robust high-frequency response, whereas the formant-rich speech token engages the mid-frequency region more effectively than a single modulated tone.

Figure 4.3. *Frequency-matched predictive value (R^2) of AM-tone versus speech EFRs across outcomes — Severe-to-Profound HL group (n = 13). T and S denote the superior stimulus at each frequency.*



These findings support the rationale for a hybrid protocol. Rather than one stimulus type being uniformly superior, tones and speech each carry an advantage in different frequency regions; using both maximises predictive coverage across the speech spectrum and, where the two responses agree, provides a built-in check on the replicability of an individual recording, a valuable property in pediatric electrophysiology, where single recordings can be vulnerable to movement and state-related artefact.

4.5 Summary of Results

The pattern of findings can be summarised as follows. First, the aided EFR did not predict behavioral outcomes in children with moderate-to-moderately-severe hearing loss, consistent with a ceiling effect under good aided audibility. Second, in children with severe-to-profound hearing loss, the aided EFR was a reliable, frequency-specific predictor of aided thresholds, accounting for up to half the variance in low to mid frequencies, and two thirds of the variance at the high frequencies, and was additionally associated with receptive and expressive language age. Third, AM-tone and speech EFRs proved complementary- tones most informative at 4000 Hz and speech most informative at 2000 Hz, supporting the combined use of both stimulus types within a single hybrid protocol.

Chapter V

Discussion

The present study aimed to evaluate the clinical utility of a hybrid envelope following response (EFR) protocol, one that combined frequency-specific amplitude-modulated (AM) tonal stimuli with an ecologically valid speech token, for the objective assessment of hearing aid benefit in children with sensorineural hearing loss. Three findings stand out. First, the predictive value of the aided EFR depended strongly on the degree of hearing loss: amplitude was unrelated to behavioral outcomes in the moderate-to-moderately-severe group but was a robust, frequency-specific predictor of aided thresholds in the severe-to-profound group. Second, tonal and speech EFRs proved complementary rather than redundant, each carrying an advantage in a different frequency region. Third, EFR amplitude was associated with receptive and expressive language age. Each of these findings is discussed below in relation to the existing literature.

5.1 Why EFR Prediction Depends on the Degree of Hearing Loss

Perhaps the most striking outcome was the contrast between the two groups. In the moderate-to-moderately-severe group, EFR amplitude did not predict aided thresholds at any frequency for either stimulus type, with all models accounting for negligible variance. In the severe-to-profound group, by contrast, every frequency-matched model showed a negative slope, indicating that larger EFR amplitudes were associated with better (lower) aided thresholds, the direction expected if stronger neural encoding reflects greater aided audibility.

This pattern is most parsimoniously explained as a ceiling effect. The aided EFR is fundamentally a measure of audibility: its amplitude and detectability rise with sensation level, and the degree of aided improvement tracks the change in behavioral thresholds between unaided and aided conditions (Easwar et al., 2015, 2023). When amplification already restores good audibility, as is typically achievable in moderate losses, children cluster near the top of that function, the between-child variance in encoding is compressed, and little covariance remains for the EFR to capture. In severe-to-profound loss, where aided audibility is more variable and frequently incomplete at the higher frequencies, the same measure has room to vary and therefore tracks threshold differences far more sensitively. This interpretation is consistent with the sensation-level dependence of aided EFRs reported by Easwar et al. (2023) and with the observation that EFR sensitivity to audibility is highest precisely where audibility is in question.

A second, complementary mechanism may also contribute. Both animal and human work has shown that sensorineural hearing loss can be accompanied by enhanced neural encoding of the temporal envelope, even as fine-structure coding degrades (Anderson et al., 2013; Ananthakrishnan et al., 2016). To the extent that more severe loss is associated with this exaggerated envelope representation, the severe-to-profound group may express a wider, more informative range of EFR amplitudes than the moderate group, further sharpening the brain-behavior relationship in exactly the population in which it was observed.

5.2 Tonal and Speech EFRs Are Complementary, Not Redundant

Although the AM-tone and speech EFRs were themselves highly correlated at each frequency, formal tests for the difference between dependent correlations were underpowered at the present sample size and did not reach significance. The descriptive pattern of explained variance, however, was systematic and clinically informative. AM tones were the stronger predictor at 4000 Hz, outperforming speech by as much as 0.32 in R^2, whereas the speech token was the stronger predictor at 2000 Hz, outperforming tones by up to 0.27 in R^2; at 500 and 1000 Hz the two performed comparably.

This double dissociation aligns with the acoustic properties of the stimuli and with prior frequency-specific findings. A clean, fully modulated tonal carrier provides a robust, spectrally concentrated drive in the high-frequency region, where fricative energy in natural speech is comparatively sparse and detectability has been shown to vary (Easwar et al., 2020; Easwar, Purcell, et al., 2022). Conversely, the speech-like modulation envelope may engage the mid-frequency region more effectively than a single modulated tone (Easwar et al., 2024). The practical implication is that neither stimulus is uniformly superior; each contributes unique predictive coverage. This is the empirical basis for a hybrid protocol, and it converges with evidence that combining multiple EFR measures improves audibility detection relative to any single response (Chesnaye et al., 2026). A further benefit follows where the two responses agree: their convergence offers a built-in replicability check on an individual recording, a valuable safeguard in pediatric electrophysiology, where single recordings are vulnerable to movement and state-related artifacts.

5.3 EFR Amplitude and Language Development

In the severe-to-profound group, EFR amplitudes were positively correlated with both receptive and expressive language age, with the high-frequency responses (the 4000 Hz tone and the 2000 Hz speech EFR) emerging as the strongest correlates. This extends the EFR literature in a meaningful direction. Previous work has linked aided EFRs to audibility and to speech discrimination (Easwar et al., 2015, 2023) and has shown that neural envelope tracking predicts speech intelligibility and hearing aid benefit in children (Van Hirtum et al., 2023); the relationship with broader, standardized language development, however, has remained largely unexplored. The present results provide preliminary evidence that aided neural encoding carries information relevant not only to momentary audibility but to longer-term communicative development.

Interpreted cautiously, this positions the aided EFR not as a passive marker of how long a child has worn hearing aids, but as a measure of the functional neural consequence of that auditory experience, and it is this encoding quality that appears to support emerging language. Such a reading is coherent with the broader role of envelope encoding in speech understanding (Purcell et al., 2004; Easwar et al., 2024). However, all the measures were cross-sectional and the causal direction cannot be established here.

5.4 Speech Detection Threshold and Ling-6 Detection

Two additional observations are worth noting. The speech detection threshold did not correlate meaningfully with EFR amplitude in either group, which is unsurprising given that a single detection threshold conflates information across the spectrum and is therefore poorly matched to the frequency-specific nature of the EFR. Similarly, Ling-6 sound detection correlated moderately-to-strongly with aided thresholds at every frequency rather than preferentially with each sound's dominant spectral region. In this severe-to-profound sample, with its highly intercorrelated audiometric configuration, Ling-6 detection therefore largely indexed overall aided audibility rather than frequency-specific audibility, and added little beyond the aided audiogram. The frequency specificity that the protocol seeks is consequently better served by the EFR than by behavioral detection screens.

5.5 Clinical Implications

The clinical value of these findings is concentrated in the group for whom it matters most. Children with severe-to-profound hearing loss are precisely those in whom behavioral verification of hearing aid benefit is hardest to obtain reliably, yet it is in this group that the aided EFR functioned as a frequency-specific, objective index of aided audibility, accounting for up to two-thirds of the variance in high-frequency thresholds. Because the responses can be recorded passively while a child watches a silent video, in clinically feasible test times, the protocol is realistic for young or difficult-to-test children (Easwar et al., 2015, 2023). The complementarity of tones and speech supports running both within a single hybrid session: tones for the high-frequency estimate, speech stimuli for the mid-frequency estimate, and their agreement as a confidence check. The association with language age, if replicated, further raises the possibility that aided EFRs could contribute to prognostic, and not only descriptive, information during pediatric hearing aid management.

5.6 Conclusion

Taken together, the results indicate that an aided hybrid EFR protocol provides a clinically useful, frequency-specific index of hearing aid benefit in children with severe-to-profound sensorineural hearing loss, the population in which objective verification is most needed. Tonal and speech stimuli contributed complementary information across the speech spectrum, supporting their combined use, and EFR amplitude was additionally associated with language development beyond the influence of age. These findings support continued development of objective EFR-based tools for pediatric hearing aid verification, while highlighting the need for larger, longitudinal studies to confirm and extend them.

Chapter VI

Summary and Conclusion

The present study investigated the clinical utility of a hybrid Envelope Following Response (EFR) protocol combining frequency-specific amplitude-modulated (AM) tonal stimuli with ecologically valid speech stimuli for objective assessment of hearing aid benefit in children with sensorineural hearing loss. The impetus for this work lies in a well-recognized clinical gap: while hearing aids are the primary rehabilitative intervention for pediatric hearing loss, verifying their benefit objectively—especially in young or difficult-to-test children—remains a significant challenge.

Twenty-six children aged 3–5 years with bilateral congenital sensorineural hearing loss who were regular hearing aid users participated in the study. They were assigned to two groups based on degree of hearing loss: a moderate-to-moderately-severe group and a severe-to-profound group, with 13 participants in each. All children underwent aided audiometry, language evaluation using the Assessment Checklist for Speech-Language Skills (ACSLS), and aided EFR recordings using both AM tonal and speech stimuli presented at 65 dB SPL through a calibrated loudspeaker under free-field conditions. Carrier frequencies of 500, 1000, 2000, and 4000 Hz were used, each modulated at a unique frequency to allow simultaneous frequency-specific extraction. Associations between log-transformed EFR amplitudes and behavioral measures were examined through Pearson correlations and simple linear regression, conducted separately for each group.

6.1 Key Findings

Three principal findings emerged. First, the predictive value of aided EFR was strongly dependent on the degree of hearing loss. In the moderate-to-moderately-severe group, EFR amplitude did not predict aided thresholds at any frequency for either stimulus type—an outcome most parsimoniously explained by a ceiling effect, where amplification typically restores good audibility and compresses between-child variance in neural encoding. In the severe-to-profound group, by contrast, frequency-matched EFR amplitudes were reliable and clinically meaningful predictors of aided thresholds across all four carrier frequencies, with the 4000 Hz AM-tone EFR alone accounting for 66% of the variance in the 4000 Hz aided threshold, and the 2000 Hz speech EFR explaining 60% of variance at 2000 Hz.

Second, AM-tone and speech EFRs proved complementary rather than interchangeable. Tonal stimuli were the stronger predictor at 4000 Hz, while the speech token outperformed tones at 2000 Hz; performance was broadly equivalent at 500 and 1000 Hz. This dissociation reflects the acoustic properties of the respective stimuli and provides an empirical rationale for the hybrid protocol: each stimulus type contributes unique predictive information in different frequency regions, and when both are used together, their convergence also serves as a built-in reliability check on individual recordings—a property of particular value in pediatric electrophysiology where movement and state-related artifacts are common.

Third, in the severe-to-profound group, EFR amplitudes were positively associated with both receptive and expressive language age, with the strongest correlates emerging at high frequencies (4000 Hz AM tone; 2000 Hz speech EFR). This extends the existing EFR literature by linking aided neural encoding not only to audiometric outcomes and speech discrimination, but also to broader language development assessed through standardized measures. Although the cross-sectional design precludes causal inference, the pattern is consistent with a pathway in which hearing aid amplification enhances audibility, which in turn supports neural encoding quality, which in turn contributes to language acquisition.

6.2 Clinical Significance

The clinical relevance of these findings is most pronounced for children with severe-to-profound hearing loss—the very population in which behavioral verification of hearing aid benefit is hardest to achieve and in which the consequences of inadequate amplification are most serious. The hybrid EFR protocol demonstrated that objective, frequency-specific indices of aided audibility can be obtained passively while a child watches a silent video, in clinically feasible recording times. The complementary contributions of tonal and speech stimuli mean that both can be incorporated within a single session without substantially increasing test time, providing wider spectral coverage than either alone. Moreover, the association between aided EFR amplitude and language age, if replicated in larger prospective studies, raises the prospect that EFRs could serve a prognostic function—informing clinicians not only about current audibility but about the likely trajectory of communicative development.

6.3 Limitations

These conclusions must be interpreted within the study's limitations. The sample was small (n = 13 per group) and drawn by convenience sampling, which constrains generalizability and left the study statistically underpowered for formal comparison of the dependent tonal and speech correlations. The cross-sectional, correlational design cannot establish causation; longitudinal data are required to determine the direction of any pathway linking neural encoding to language development. Testing was monaural, conducted only in the aided condition of the better ear, without an unaided comparison, so the findings describe associations among aided measures rather than aided-versus-unaided change. Language was estimated using a checklist-based tool rather than a comprehensive standardized battery, and the EFR–language associations should accordingly be regarded as preliminary.

6.4 Directions for Future Research

Future studies should prioritize larger and more representative samples to improve generalizability and provide adequate statistical power to formally test whether tonal and speech EFRs differ in predictive value at specific frequencies. Longitudinal designs tracking EFR amplitude alongside language growth would allow the proposed auditory experience–neural encoding–language pathway to be examined directly. Including both aided and unaided recording conditions would allow the protocol to be used as a true change measure and potentially improve its sensitivity. Extending the paradigm to cochlear implant users—a population in which EFR-type measures remain underexplored—would broaden its clinical reach.

6.5 Conclusion

This study demonstrates that a hybrid EFR protocol—combining frequency-specific AM tonal stimuli with speech stimuli—can serve as a clinically viable, objective measure of hearing aid benefit in children with sensorineural hearing loss. Its utility is most clearly established in the severe-to-profound group, precisely the population for whom behavioral verification is most challenging and most critical. The two stimulus types contributed complementary frequency-specific information, arguing for their combined use in a single hybrid session, and EFR amplitude was additionally associated with language development beyond the effect of chronological age.

Hearing loss in early childhood carries lasting consequences for language, communication, and learning. The availability of objective tools that can confirm whether amplification is reaching and engaging the auditory system in a meaningful way is therefore not merely a technical convenience—it is a clinical necessity. The present findings represent a step toward embedding such tools in routine pediatric hearing aid management. With further validation through larger longitudinal studies, aided EFR protocols have the potential to strengthen the evidence base for individualized amplification decisions and, ultimately, to improve outcomes for children who depend on hearing aids from the earliest years of life.

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Appendix

Table A1

Shapiro-Wilk Test of Normality across variables in children with Moderate to Moderately Severe Hearing Loss (n = 13)

Variable	*W*	*n*	*p*
INTERV_AGE	.989	13	.999
LISTEN_AGE	.851	13	.029
RLA_m	.749	13	.002
ELA_m	.748	13	.002
/a/	.905	13	.158
/i/	.846	13	.026
/u/	.915	13	.212
/m/	.903	13	.147
/s/	.833	13	.017
/ʃ/	.906	13	.161
A_500	.893	13	.107
A_1000	.906	13	.163
A_2000	.953	13	.641
A_4000	.880	13	.071
SDT	.849	13	.028
log_T_500_NF_A	.836	13	.019
log_S_500_NF_A	.963	13	.793
log_T_1000_NF_A	.918	13	.235
log_S_1000_NF_A	.857	13	.035

log_T_2000_NF_A	.809	13	.009
log_S_2000_NF_A	.955	13	.679
log_T_4000_NF_A	.915	13	.213
log_S_4000_NF_A	—	—	—

Note. *W* = Shapiro-Wilk statistic; *n* = sample size; *p* = two-tailed significance. INTERV_AGE = age at intervention; LISTEN_AGE = listening age; RLA_m = receptive language age (months); ELA_m = expressive language age (months); /a/, /i/, /u/, /m/, /s/, /ʃ/ = phoneme accuracy scores; A_500–A_4000 = audiometric thresholds at 500–4000 Hz; SDT = speech detection threshold; log_T/S_[freq]_NF_A = log-transformed target/stimulus scores at specified frequencies (no-filter condition, aided). log_S_4000_NF_A had insufficient data for normality testing (denoted by —). Several variables yielded significant Shapiro-Wilk statistics (*p*s < .05), indicating departure from normality; these variables should be interpreted with caution or analysed using non-parametric alternatives.

Table A2

Shapiro-Wilk Test of Normality across variables in children with Severe to Profound Hearing Loss (n = 13)

Variable	*W*	*n*	*p*
Severity	0	13	< .001
INTERV_AGE	.965	13	.833
LISTEN_AGE	.913	13	.201
RLA_m	.924	13	.285
ELA_m	.926	13	.304
/a/	.921	13	.261
/i/	.903	13	.147
/u/	.940	13	.454
/m/	.955	13	.676
/s/	.928	13	.319
/ʃ/	.943	13	.496
A_500	.943	13	.501
A_1000	.904	13	.150
A_2000	.937	13	.420
A_4000	.902	13	.143
SDT	.908	13	.170
log_T_500_NF_A	.910	13	.183
log_S_500_NF_A	.935	13	.390
log_T_1000_NF_A	.891	13	.099
log_S_1000_NF_A	.903	13	.146
log_T_2000_NF_A	.874	13	.059

log_S_2000_NF_A	.858	13	.036
log_T_4000_NF_A	.914	13	.209
log_S_4000_NF_A	.882	13	.076

Note. *W* = Shapiro-Wilk statistic; *n* = sample size; *p* = two-tailed significance. INTERV_AGE = age at intervention; LISTEN_AGE = listening age; RLA_m = receptive language age (months); ELA_m = expressive language age (months); /a/, /i/, /u/, /m/, /s/, /ʃ/ = phoneme accuracy scores; A_500–A_4000 = audiometric thresholds at 500–4000 Hz; SDT = speech detection threshold; log_T/S_[freq]_NF_A = log-transformed target/stimulus scores at specified frequencies (no-filter condition, aided). Severity was a categorical variable; normality testing was not applicable (*W* not computed). All continuous variables yielded non-significant Shapiro-Wilk statistics (*p*s > .05), supporting the assumption of normality within Group 1.