# Effect of Contralateral Acoustic Stimulation on Frequency Following Responses to Speech and Complex Tone

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**Registration No: P01II24S023041**

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(Audiology)

University of Mysore


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**June, 2026**

## CERTIFICATE

This is to certify that this dissertation entitled **"Effect of Contralateral Acoustic Stimulation on Frequency Following Responses to Speech and Complex Tone"** is a bonafide work submitted as part of fulfilment of the degree of Master of Science **Audiology** of the student with Registration Number **P01II24S023041**. 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 **"Effect of Contralateral Acoustic Stimulation on Frequency Following Responses to Speech and Complex Tone"** 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.

Mysuru
June, 2026

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# DECLARATION

This is to certify that this dissertation entitled **"Effect of Contralateral Acoustic Stimulation on Frequency Following Responses to Speech and Complex Tone "** is the result of my own study under the guidance of **Dr. Ajith Kumar U, 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.

Mysuru
June, 2026

**Registration no. P01II24S023041**

# DEDICATION

WITH LOVE & GRATITUDE

Nanu · Nani

Daddy · Mummy

*& my dearest Laali*

*whose love, endless encouragement, and quiet sacrifices made this journey possible. Every step of this work was carried forward by their strength and belief in me. Without them, none of this would have been possible.*

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## ABSTRACT

The auditory brainstem's capacity to encode the fundamental frequency (F0) and temporal fine structure of complex acoustic signals through sustained phase locked neural activity is foundational to both speech perception and pitch processing. This sustained neural activity is measurable as the frequency following response (FFR), which comprises two distinct components: the envelope-following response ($FFR_{ENV}$), which tracks the slowly varying periodic amplitude envelope, and the temporal fine-structure-following response ($FFR_{TFS}$), which reflects rapid, high-frequency fine structure encoding. Although the effects of ipsilateral masking noise on FFR are comparatively well documented, the neurophysiological consequences of contralateral acoustic stimulation (CAS) on subcortical speech and complex tone encoding remain insufficiently examined.

CAS is known to engage the medial olivocochlear (MOC) efferent reflex, a descending auditory pathway that modulates cochlear gain and auditory nerve output; however, whether this modulation suppresses or facilitates brainstem neural encoding is not fully established. The present study, therefore, examined how CAS modifies the spectral amplitudes of $FFR_{ENV}$ and $FFR_{TFS}$ elicited by speech and complex tonal stimuli, and whether the physical presence of the F0 within a stimulus influences the strength of subcortical envelope encoding. Forty-one adults (18–30 years) with clinically confirmed normal peripheral hearing participated. Four stimuli were employed: a 170 ms synthetic /ba/ syllable, a 300 Hz high-pass filtered /ba/ syllable (missing F0), a 10-tone harmonic complex tone with a 260 Hz F0, and the same complex tone with its first two harmonics excluded. All stimuli were presented to the right ear at 70 dB SPL; CAS was delivered contralaterally at 60 dB SPL.

Spectral amplitudes of $FFR_{ENV}$ and $FFR_{TFS}$ were extracted using Fast Fourier Transform analysis in MATLAB, and Wilcoxon signed-rank tests were used for inferential comparison. Results demonstrated that CAS significantly enhanced $FFR_{ENV}$ amplitudes for the high-pass filtered /ba/ syllable and for both complex tone conditions, and increased $FFR_{TFS}$ amplitudes at the first formant frequency of the original /ba/ syllable, indicating a facilitatory rather than suppressive role of efferent activation. Paradoxically, removing the physical F0 from the /ba/ syllable produced significantly stronger $FFR_{ENV}$ amplitudes compared to the original stimulus, while no significant difference was observed between complex tone conditions with and without the physical F0. Collectively, these findings reveal that CAS exerts stimulus-specific modulatory influences on subcortical neural encoding, and that brainstem F0 representation relies on higher-order harmonic interactions rather than direct acoustic energy at the F0.

# CHAPTER 1

## INTRODUCTION

The term Frequency Following Response (FFR) was originally coined by Worden & Marsh (1968). It is a measure of synchronous sound-evoked brainstem activity that reveals the integrity of sound processing in the brainstem and reflects auditory-neurophysiological processes with granularity and precision rarely offered by other tests in human neuroscience (Russo et al., 2004). It is characterised by a slowly varying periodic envelope and rapidly varying frequency components contained in the envelope, referred to as the temporal fine structure. The FFR reflects neural phase-locked activity that resembles the eleciting stimulus (Kraus et al., 2017). The stimulus and response are similar with respect to duration, periodicity, and rise. Thus, the FFR is a test to evaluate the neural coding of multiple features in sound. It is well known that phase-locked neural activity occurs throughout the auditory brainstem up to the inferior colliculus (Kraus et al., 2017). Attempts have been made at isolating FFR sources, but results have been conflicting. The reason may be that FFR may be complex of several distinct components arising from multiple generators. What distinguishes the FFR from other types of sound-evoked neurophysiologic responses is that an individual's FFR offers a wealth of information about sound processing in the brainstem- a biological mosaic that goes far beyond the timing and amplitude measures gleaned from most types of sound evoked neural activity.

Pitch is important for speech and music perception, and may also play a crucial role in our ability to segregate sounds that arrive from different sources. Data from normal-hearing listeners suggest that the low-frequency, low-numbered harmonics within complex tones are of prime importance in pitch perception and in the perceptual segregation of competing sounds (Oxenham, 2008). In human listeners, a tone complex comprised of

successive harmonics of a fundamental frequency ($F_0$), but having no acoustic energy at the $F_0$, evokes a pitch corresponding to the missing $F_0$. This phenomenon is known as the "pitch of the missing fundamental" and is a well-established attribute of human pitch perception. The pitch of the missing $F_0$ remains unchanged when the tone complex is presented in a background of masking noise centered on the $F_0$ (Shofner, 2011).

FFR measures are related to the ability to differentiate sounds, hear targets in noise. Listening in **background noise** is one of the most demanding auditory tasks. Studies consistently report that the presence of noise reduces the stability of neural phase-locking and decreases the amplitude of FFRs, reflecting a decline in the precision with which speech cues are encoded (Yellamsetty & Bidelman, 2019). While ipsilateral masking noise presented in the same ear as the stimulus has been widely investigated, the effects of **contralateral masking** are comparatively under-explored.

The presence of masking noise disrupts the encoding of auditory signals by interfering with cochlear travelling waves and reducing the availability of neurotransmitters at the inner hair cell–auditory nerve synapse (Delgutte, 1990). From a perceptual perspective, masking noise leads to increased detection thresholds and reduced accuracy in discriminating speech sounds (Smith & Cone, 2021).

Contralateral stimulation is of special interest because it engages the **olivocochlear efferent system,** a descending auditory pathway that regulates cochlear activity and modulates neural coding at subcortical levels (Guinan, 2006).

**Need for the Study**

FFR will provide a non-invasive way to study how the auditory brainstem encodes both the envelope and temporal fine structure of speech and tonal signals. Because it

preserves the fundamental frequency and temporal features of speech, it will provide a sensitive measure of auditory processing in both quiet and noisy conditions (Skoe & Kraus, 2010).

In the present investigation, we propose to record FFRs to speech and complex tone stimuli, both with and without the $F_0$ physically present. It is well established that even in the absence of a physical $F_0$, listeners can perceive pitch through the harmonic structure of the sound (Matsuwaki et al., 2004). FFRs are known to encode both the envelope (reflecting the $F_0$) and the temporal fine structure of the stimulus (Ananthakrishnan et al., 2016). However, the encoding of the envelope in the absence of a physical $F_0$ has not been extensively studied. The present study, therefore, aims to compare the encoding of the envelope for the speech syllable /ba/ and a 10-tone harmonic complex with and without the physical presence of $F_0$.

Contralateral noise is known to reduce cochlear amplification through the medial olivocochlear reflex (MOCR) (Kumar & Vanaja, 2004). Emerging evidence suggests that contralateral stimulation may exert a suppressive influence on auditory brainstem activity (Usubuchi et al., 2014). However, it is not yet clear whether modulation of cochlear gain via the MOCR has differential effects on the encoding of the temporal envelope and fine structure. Accordingly, the present study also proposes to investigate the effect of contralateral noise on the spectral amplitudes of FFRs corresponding to the envelope and the fine structure.

**Aim of the Study**

The present study aims to examine the effect of CAS on FFRs elicited by speech stimuli and complex tone.

## Objectives of the Study

Specific objectives of the current investigation are

1. To compare the spectral amplitude of $FFR_{ENV}$ and $FFR_{TFS}$ in the presence and absence of CAS for:
    a. Original /ba/ syllable
    b. 300 Hz high-pass filtered /ba/ syllable
2. To compare the spectral amplitude of $FFR_{ENV}$ elicited by original /ba/ and 300 Hz high-pass filtered /ba/
3. To compare the spectral amplitude of $FFR_{ENV,}$ in the presence and absence of CAS for
    a. Complex tone with 260 Hz $F_0$
    b. Complex tone with 260 Hz $F_0$ excluding the first two harmonics
4. To compare the spectral amplitude of $FFR_{ENV}$ elicited by the complex tone with and without F0.

## Null Hypothesis ($H_0$):

1. There is no significant difference in the spectral amplitude of $FFR_{ENV}$ and $FFR_{TFS}$ between the presence and absence of CAS, both for the original /ba/ syllable and for the 300 Hz high-pass filtered /ba/ syllable.
2. There is no significant difference in the spectral amplitude of $FFR_{ENV}$ elicited by the original /ba/ syllable and the 300 Hz high-pass filtered /ba/ syllable.
3. There is no significant difference in the spectral amplitude of $FFR_{ENV}$ between the presence and absence of CAS, both for the complex tone with 260 Hz

fundamental frequency and for the complex tone with 260 Hz fundamental frequency excluding the first two harmonics.

4. There is no significant difference in the spectral amplitude of $FFR_{ENV}$ elicited by the complex tone with $F_0$ and the complex tone without $F_0$.

# CHAPTER 2

# REVIEW OF LITERATURE

The frequency-following response (FFR) is a neurophysiological signal recorded from Krizman and Kraus (2019). The FFR captures phase-locked neural activity that relates to key acoustic features, such as the periodicity envelope (F0) and temporal fine structure (TFS). These features are crucial for understanding pitch and speech (Ananthakrishnan et al., 2016). The FFR shows strong encoding of these features in people with normal hearing. However, its shape and timing are very sensitive to background noise and sensorineural hearing loss (Ananthakrishnan et al., 2016; Parbery-Clark et al., 2009). On the positive side, experience and training can change this neural representation, helping to reduce the negative impact of background noise on processing in the brainstem (Parbery-Clark et al., 2009). Overall, the FFR provides an important clinical and research tool for studying human communication and the biology of hearing (Kraus et al., 2017; Krizman & Kraus, 2019).

## Frequency-Following Responses and Pitch Encoding

The FFR represents an electrophysiologically evoked potential that primarily captures sustained subcortical neural activity in response to periodic acoustic stimulation (Durante & Oliveira, 2020; Jeng et al., 2021). Early animal research initially identified and recorded these phase-locked neural responses within the central auditory pathways of cats (Ribarić et al., 1984). Subsequent investigations successfully expanded this methodology to human subjects, demonstrating that corresponding bioelectrical potentials could be recorded non-invasively from the scalp surface (Ribarić et al., 1984). Physiological evidence indicates that the primary neural generator of this human scalp-recorded potential is localized within the inferior colliculus of the brainstem, though secondary peripheral contributions from cochlear microphonics remain a subject of discussion (Ribarić et al., 1984). Functionally, the

FFR is widely recognized as a highly reliable mechanism for transmitting precise information regarding both the F0 and the overarching waveform characteristics of an incoming acoustic signal (Ribarić et al., 1984).

A foundational dimension of brainstem auditory processing is its capacity to track and encode pitch relevant information with remarkable temporal precision (Jeng et al., 2021). Study established that the FFR directly preserves the essential pitch-relevant components necessary for speech intelligibility. Their findings demonstrated that resolved harmonics generate significantly stronger neural periodicity within the subcortical pathway than their unresolved counterparts (Galbraith et al., 1995). Furthermore, the underlying brainstem neural patterns successfully track complex acoustic alterations, such as pitch doubling when alternating phase stimuli are presented to the listener (Galbraith et al., 1995). These combined insights reveal that the amplitude and periodic structure of the FFR reflect the qualitative fidelity of auditory encoding rather than serving merely as an index of general response magnitude (Galbraith et al., 1995). The processing of pitch shifts and complex tonal structures is intrinsically linked to this neural detection of periodicity within the sound waveform (Cariani & Delgutte, 1996; Järveläinen et al., 2002). When acoustic signals exhibit inharmonicity, the subcortical auditory pathways experience greater difficulty in extracting clean periodicity cues, which can induce pitch ambiguity (Järveläinen et al., 2002).

In contemporary research, the FFR has evolved into an invaluable objective tool for evaluating subcortical responses to complex, non-linear signals such as human speech, which cannot be adequately modeled using standard click stimuli (Durante & Oliveira, 2020). For instance, when utilizing a speech syllable like /da/, the evoked FFR maps out a series of highly distinct morphological components specifically waves V, A, C, D, E, F, and O which neatly parallel the transient onset/offset boundaries and the sustained vowel

portions of the acoustic token (Durante & Oliveira, 2020). However, the absolute fidelity of this subcortical frequencycoding framework is heavily vulnerable to external acoustic degradation, particularly in noisy or reverberant listening environments (Jeng et al., 2021). While the detrimental effects of ipsilateral noise are well-documented to suppress spectral energy and degrade structural response characteristics, studying the effects of contralateral acoustic stimulation (CAS) illuminates the active role of bilateral and communicative central auditory pathways (Jeng et al., 2021; Song et al., 2011). Recent findings reveal that the introduction of continuous white noise to the contralateral ear significantly degrades frequency-coding accuracy at the subcortical level in normal-hearing adults (Jeng et al., 2021). This specific contralateral interference leads to a measurable reduction in frequency tracking accuracy and a significant increase in slope error metrics during vowel perception (Jeng et al., 2021). These insights demonstrate that contralateral acoustic inputs trigger active modulatory or inhibitory pathways that directly alter subcortical processing, providing a vital physiological foundation for future investigations into the effects of CAS on speech-evoked brainstem responses (Durante & Oliveira, 2020; Jeng et al., 2021).

**The Medial Olivocochlear Reflex and Contralateral Suppression of OAE**

The central auditory system features network of descending neural pathways that modulate peripheral sensory processing via top-down feedback loops (Giraud et al., 1995). Within this framework, the caudal efferent pathway is predominantly driven by the medial olivocochlear (MOC) bundle, which originates in the superior olivary complex of the brainstem and directly terminates on the outer hair cells (OHCs) of the cochlea (Gafoor & Uppunda, 2024; Giraud et al., 1995). In complex and noisy environments, the auditory system uses the MOC efferent reflex to inhibit cochlear amplification and adjust auditory gain. The acoustic MOC reflex often activates when sound is presented to the opposite ear. This

process is called CAS (Lilaonitkul & Guinan, 2009). Which activates this MOC loop and modifies active micromechanical responses within the organ of Corti (Gafoor & Uppunda, 2024).

Animal studies have shown that providing continuous or transient sound to the opposite side can reduce the responses of auditory-nerve afferents to sounds on the same side. This effect is directly controlled by cochlear efferents (Warren & Liberman, 1989). This physiological mechanism is routinely and non-invasively tracked by evaluating the contralateral suppression of otoacoustic emissions (OAEs), which typically results in a clear reduction of the recorded OAE amplitude (Collet et al., 1994; Gafoor & Uppunda, 2024). Because OAEs are direct acoustic expressions of OHC electromotility, measuring variations in these emissions during CAS serves as a valuable proxy for quantifying the inhibitory strength of the uncrossed MOC system (Gafoor & Uppunda, 2024; Giraud et al., 1995).

Historically, the underlying mechanism driving contralateral OAE suppression was a subject of considerable debate, with early studies questioning whether the observed amplitude reductions resulted from true inner ear efferent activity or middle ear acoustic reflex pathways (Gafoor & Uppunda, 2024) .Clinical investigations using pathological human models have since confirmed that the stapedius reflex is not a prerequisite for obtaining this suppressive effect (Collet et al., 1994; Gafoor & Uppunda, 2024).

Examining the acoustic properties of contralateral suppression demonstrates that CAS causes modifications to the OAE response profile, including notable phase advances and upward frequency shifts in spontaneous emissions (Gafoor & Uppunda, 2024). Furthermore, this suppressive interaction respects a highly precise tonotopic distribution along the cochlea, meaning that narrow-band contralateral noise selectively dampens the specific OAE

frequencies contained within the spectral composition of the eliciting sound (Collet et al., 1994; Gafoor & Uppunda, 2024).

In humans, MOC activation and the resulting contralateral suppression can be triggered by noise bands (Guinan, 2006). Clinically, this suppression is often assessed using transient-evoked otoacoustic emissions (TEOAEs). However, other measures indicate that contralateral suppression is significantly stronger when using the auditory steady-state response (ASSR) (Mertes & Leek, 2016). Using these different measures helps accurately describe the frequency-specific feedback from the MOC reflex in both normal and impaired ears (Lilaonitkul & Guinan, 2009; Mertes & Leek, 2016). From a functional perspective, the activation of the MOC efferent loop provides anti-masking benefit by attenuating peripheral responses to continuous background noise, thereby theoretically enhancing subcortical signal-to-noise ratios for transient speech tokens (Giraud et al., 1995)

***Influence of Contralateral acoustic Stimulation on Brainstem and Neural Processing***

Beyond the cochlea and auditory nerve, CAS exerts a suppressive influence on higher order central auditory responses. Research utilizing magnetoencephalography (MEG) has observed the effects of contralateral noise on oscillatory brain responses, specifically demonstrating a significant suppression of the 20-Hz Auditory study state response (ASSR) (Usubuchi et al., 2014). Because the 20-Hz ASSR reflects phase-locked brainstem activity, these findings suggest that contralateral noise induces a modulatory "gain control" effect directly on subcortical structures (Usubuchi et al., 2014). FFR relies on precise temporal processing to encode sound faithfully (Ananthakrishnan et al., 2016). Disruptions to this temporal precision whether from background noise, sensorineural hearing loss, or altered efferent feedback result in delayed neural timing and degraded response morphology (Ananthakrishnan et al., 2016; Parbery-Clark et al., 2009). Therefore, the application of

contralateral noise during neurophysiological recordings serves as a powerful method to isolate the efferent system's role in modulating brainstem representations of complex sounds (Usubuchi et al., 2014).

**Conclusion**

FFR is far more than a routine electrophysiological measure it is a precise readout of how faithfully the brainstem reconstructs the acoustic architecture of speech and other complex sounds, from moment-to-moment pitch contours to the fine temporal texture of vowels (Durante & Oliveira, 2020; Krizman & Kraus, 2019). Across decades of research, one truth has held steady: subcortical pitch processing depends on highly synchronized neural firing, and what the FFR shows us is not just whether the brain responded, but how well it kept up with the signal (Ananthakrishnan et al., 2016; Galbraith et al., 1995). The trouble is that this careful neural synchrony does not hold up well under acoustic pressure when noise enters from the opposite ear, the brainstem's ability to track frequency information falters in measurable and meaningful ways (Jeng et al., 2021). This vulnerability is closely tied to the MOC efferent system, which functions as the auditory system's own volume regulator, dialling down cochlear amplification when CAS is applied a reflex that can be tracked non invasively through reductions in OAE amplitude (Gafoor & Uppunda, 2024; Giraud et al., 1995; Collet et al., 1994). What is especially relevant to the present dissertation is the growing evidence that this efferent influence does not stop at the cochlea it reaches into the brainstem itself, actively suppressing the phase-locked activity that the FFR depends on (Lilaonitkul & Guinan, 2009; Usubuchi et al., 2014). And yet, despite how much we have learned about CAS and brainstem encoding independently, the two have rarely been examined together in the context of real speech stimuli and acoustically rich signals leaving a gap that the current investigation is well-positioned to address (Durante & Oliveira, 2020;

Jeng et al., 2021). Filling this gap matters not just scientifically but practically, since understanding how efferent pathways shape brainstem speech encoding could illuminate the neural roots of difficulty hearing in noise and point toward more precise audiological solutions (Parbery-Clark et al., 2009; Krizman & Kraus, 2019).

# CHAPTER 3

# METHODS

The present study examined the effect of contralateral acoustic stimulation (CAS) on frequency-following responses (FFR) elicited by speech and complex tone stimuli. The FFR has two distinct components: the envelope-following response ($FFR_{ENV}$), reflecting the neural encoding of the periodicity envelope, and the fine-structure-following response ($FFR_{TFS}$), reflecting the encoding of the temporal fine structure. Both components were examined in the presence and absence of CAS. Additionally, the study explored whether the neural encoding of the envelope differed when the physical fundamental frequency (F0) was present versus absent in the stimulus. The speech syllable /ba/ and a 10-tone harmonic complex tone served as the stimuli, allowing a comparison of brainstem responses across two acoustically distinct signal types.

## Research Design and Sampling

A within-subjects repeated-measures design was employed for this investigation (Schiavetti & Metz, 2006). Each participant was assessed under both listening conditions—with and without CAS allowing direct comparisons of FFR amplitudes within the same individual and thereby controlling for biological variability across participants. The number of participants required to achieve statistical significance ($\alpha = .05$) and adequate power ($1-\beta = .80$) was determined to be 41, calculated a priori using G*Power 3.1 software (Faul et al., 2007). Sample size estimation was based on effect sizes drawn from a comparable paired-comparisons paradigm reported in the existing literature (Smith & Cone, 2021). Participants were recruited through a purposive sampling procedure from the student population of the All India Institute of Speech and Hearing, (AIISH) Mysuru.

## Participants

A total of 41 adults aged between 18 and 30 years with clinically confirmed normal peripheral hearing took part in this study. Balanced gender representation was sought during the recruitment phase. All participants were native Kannada speakers. Prior to enrolment, each individual underwent a comprehensive audiological assessment to verify their eligibility. They were recruited based on the following inclusion and exclusion criteria.

***Inclusion Criteria***

Participants were included if they met the following conditions:

1. Air-conduction pure-tone thresholds not exceeding 15 dB HL across octave frequencies from 250 Hz to 8 kHz.
2. Speech recognition scores of at least 90% on the Phonemically Balanced Kannada word lists (Yathiraj & Vijayalakshmi, 2005).
3. Normal middle-ear function, confirmed by a type ‘A’ or ‘As’ tympanogram and the presence of acoustic reflexes at normal sensation levels.
4. Kannada reported as their mother tongue.
5. Global Transient Evoked Otoacoustic Emissions (TEOAE) amplitudes of 6 dB SPL or greater, recorded using click stimuli presented at 80 dB pe SPL.
6. No noise risk during the past year, as assessed by the 1-Minute noise screening questionnaire (Johnson et al., 2017).

***Exclusion Criteria***

Participants were excluded if they met any of the following conditions:

1. Presence of impacted cerumen or active otological conditions (e.g., otalgia, otorrhea, or tinnitus).
2. History of neurological, cognitive, speech-language, or psychological disorders as reported during the interview

**Ethical Considerations**

Before commencement of the testing, all the participants were informed regarding the procedures and purpose of the study, and written informed consent was obtained from all the participants. All the steps involved in that study adhered to the ethical guidelines for bio- behavioural research involving human subjects of AIISH, Mysuru (AIISH, 2023). The study was approved by the AIISH Institutional Review Board (Ref:SH/IRB/M.4/AUD.02/2025-26). Annexure I provides the ethical approval letter.

**Test Environment**

All tests were carried out in an acoustically and electrically shielded double room with ambient noise within the permissible limits of American National Standards Institute (ANSI S3.1,1999).

**Instrumentation**

The study used the following instruments and software's:

1. A calibrated two-channel standalone audiometer, AC40 (Interacoustics, Middelfart, Denmark), was used to evaluate the hearing status of the participants. Air-conduction thresholds, bone-conduction thresholds and speech audiometry was obtained for all participants. For air-conduction testing and speech audiometry, a DD450 high-frequency headset (Radioear, Middelfart, Denmark) was used.

2. The Titan device equipped with the IMP440 Impedance System (Interacoustics, Middelfart, Denmark) was utilised for immittance evaluation measures using a 226 Hz probe tone for tympanometry. All participants underwent acoustic reflex thresholds testing at 500 Hz, 1 kHz, 2 kHz, 4 kHz, and broadband noise (BBN) in both ipsilaterally and contralaterally for all participants.

3. A calibrated Oto Dynamics Echoport 292 II dual probe system with ILO v6 data management and analysis software (Otodynamics Ltd., London, UK) was used to record the Transient Evoked Otoacoustic Emissions (TEOAEs) and contralateral suppression of TEOAEs.

4. A calibrated four-channel evoked potential system (SmartEP, version 5.54.21; Intelligent Hearing Systems, Florida, USA) equipped with an Opti-Amp USB Box and a multi-channel Opti-Amp Transmitter 8008 was used for recording the FFR. Stimulus was presented through an ultra-shielded 300-ohm insert earphones (Intelligent Hearing Systems, Florida, and USA).

**Basic Audiological Evaluation**

1. A comprehensive case history was obtained to rule out any auditory system pathologies.
2. Otoscopic evaluation was carried out to check for impacted cerumen and other external ear abnormalities.
3. Pure-tone audiometry was performed to establish air-conduction thresholds (250 Hz–8 kHz) and bone-conduction thresholds (250 Hz–4 kHz), following the modified Hughson and Westlake procedure (Carhart & Jerger, 1959).
4. Speech identification ability was measured using Phonemically Balanced Kannada word lists (Yathiraj & Vijayalakshmi, 2005).
5. Immittance evaluation was done. Tympanometry was done using a 226 Hz probe tone and measurement of acoustic reflexes at 500 Hz, 1 kHz, 2 kHz, and broadband noise in both ipsilateral and contralateral conditions.
6. Transient Evoked Otoacoustic Emissions (TEOAEs) was recorded using 260 linear click sweeps presented at an intensity of 80 dBpeSPL.

**Recording of FFRs**

***Stimulus*:**

a) 170 ms synthetic /ba/ stimulus, hereafter referred to as the *original/ba/*.

b) The *original /ba/* stimulus filtered through a 300 Hz high-pass filter.

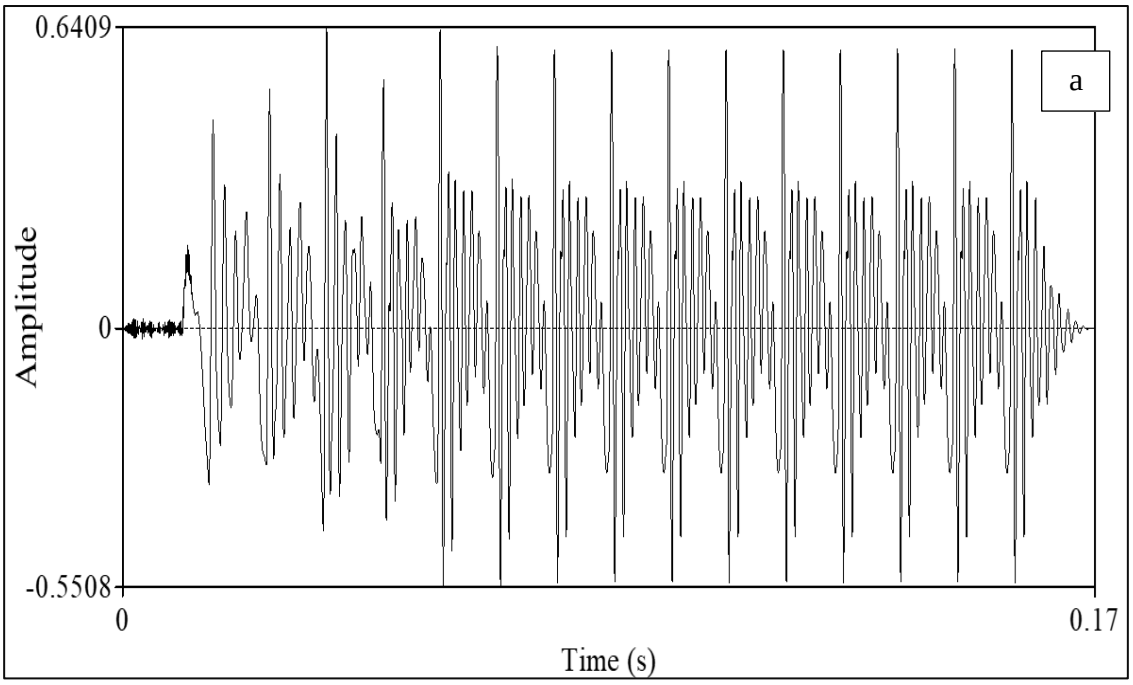
c) 10-tone harmonic complex with a fundamental frequency of 260 Hz.

d) 10-tone harmonic complex with a fundamental frequency of 260 Hz, excluding the first two harmonic components.

Figures 3.1(a) and (b) shows the waveform and spectrum of /ba/ speech stimuli. Figures 3.2 (a) and (b) shows the waveform and spectrum of complex tone stimuli. All stimuli were presented to right ear at an intensity of 70 dB SPL. CAS was presented to the left ear at 60 dB SPL using contralateral masking module of Intelligent Hearing System (IHS).

**Figure 3.1**

*Waveform(a) and spectrum(b) of 170 ms synthetic /ba/ stimulus.*



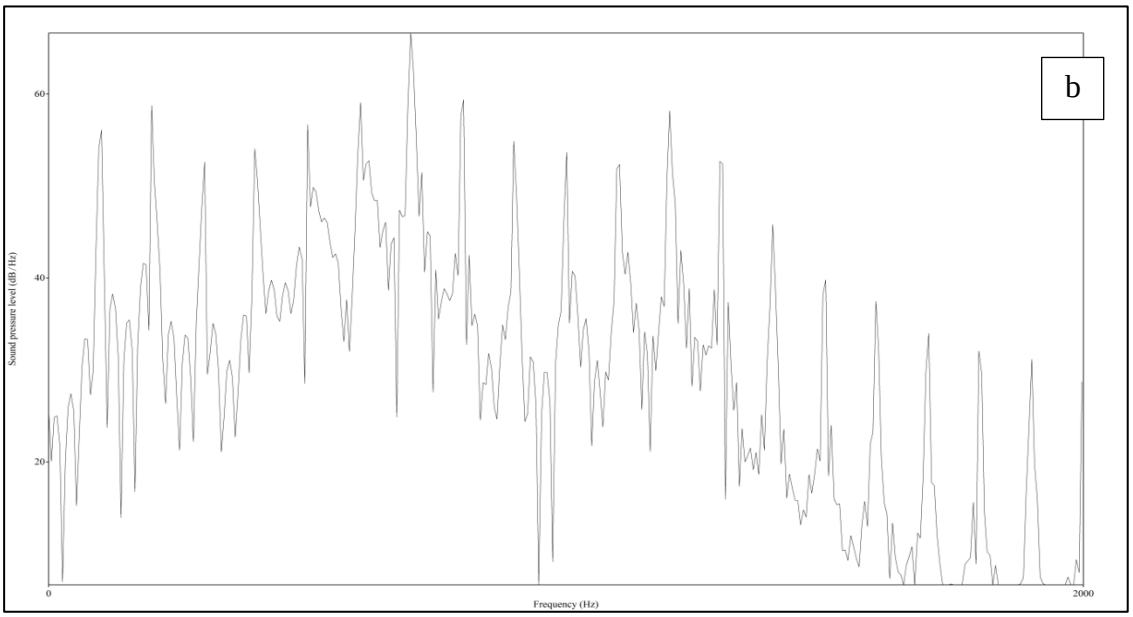
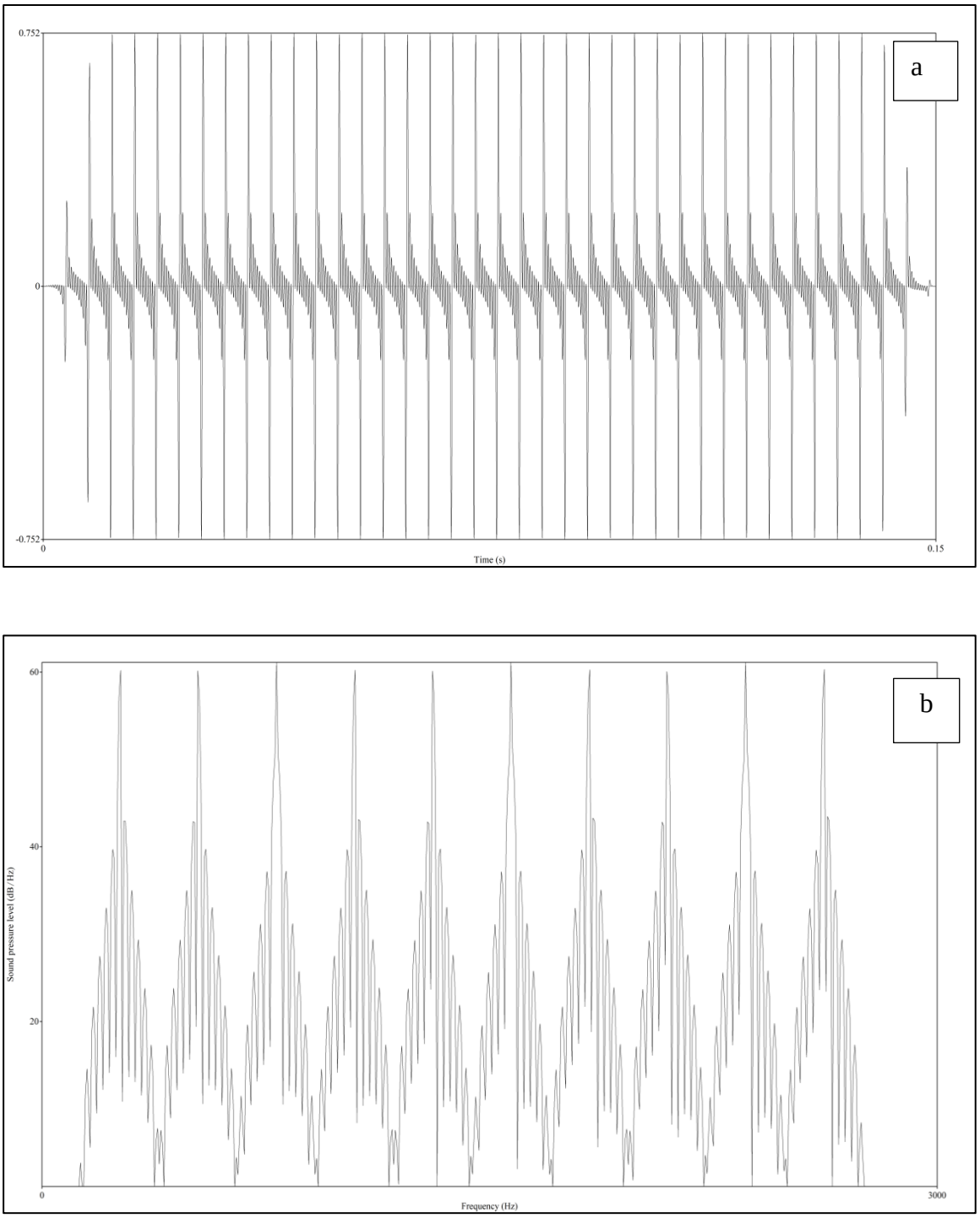



**Figure 3.2**

*Waveform (a) and spectrum (b) of 150 ms complex tone stimulus.*



***Procedure:***

All testing procedures were conducted in an electrically and acoustically treated room with noise levels below the permissible limits as recommended by ANSI S3.1–1991, R2018. FFR recordings were obtained using the Intelligent Hearing System (IHS) with smart EP software equipped with the advanced research module. Participants were seated comfortably on a reclining chair to minimize neck muscle activity. The electrode sites were cleaned with cotton using a skin preparation gel (NuPrep) before placement to minimize electrical impedance between the skin and the electrodes. A conductive paste (Ten20) was then be applied to improve signal transmission. Participants were instructed as follows: "You will hear sounds in your ear. You do not need to respond to the sounds. Please keep your eyes closed and remain relaxed throughout the testing." Recordings were obtained from the right ear of all participants. FFRs were recorded using two electrode montages:

- Vertex (Cz) referenced to right mastoid
- Vertex (Cz) Seventh cervical vertebra (C7)

The ground electrode was placed on the lower forehead (Fpz). FFRs were recorded simultaneously from both montages and averaged to enhance the signal-to-noise ratio. All electrodes absolute and inter electrode impedances were maintained below 5 kΩ and 2 kΩ respectively.

Stimuli were presented to the right ear through shielded ER-3A insert earphones at a repetition rate of 4.1/s and an intensity of 70 dB SPL. Two recordings of 1024 sweeps each was collected using alternating polarity. The averaged waveform from the two recordings was used for analysis. The responses were amplified 100,000 times with artifact rejection enabled and band-pass filtered between 50 and 3000 Hz.

***Analysis of FFR***

All FFR recordings as mentioned above were obtained using alternating stimulus polarity. The split-buffer averaging function within the IHS SmartEP software was used to store responses as condensation and rarefaction polarities separately. These were later used to obtain two components: $FFR_{ENV}$ - by summing the two polarity FFR, and $FFR_{TFS}$ - by subtracting one polarity FFR from the other.

Spectral analysis was performed using the Fast Fourier Transform (FFT) function using a custom MATLAB code. Offline filtering was done within the MATLAB code before obtaining the FFT to analyse the spectral amplitudes. For $FFR_{ENV}$ and $FFR_{TFS}$ the bandpass filter was set between 60 Hz to 1500 Hz and 100 Hz to 2000 Hz respectively. Following the offline filtering $FFR_{ENV}$ were analyzed to extract the spectral amplitude at the fundamental frequency, F0 = 100 Hz (/ba/ and /ba/ with missing F0), and F0 = 260 (complex tone and Complex tone with missing F0. The $FFR_{TFS}$ of /ba/ stimulus was analyzed to extract spectral amplitudes at frequencies corresponding to the first and second formant frequencies (700 Hz and 1200 Hz respectively). The data were initially tabulated using Microsoft Excel software.

***Statistical Analysis:***

All data were tabulated and statistically analysed using Jeffrey's Amazing Statistics Program (JASP; JASP Team, 2023). Shapiro-Wilk's test (Shapiro & Wilk, 1965) was done to check whether the data was normally distributed or non-normally distributed. Depending on weather the data is normally or non-normally distributed appropriate parametric or non-parametric statistical tests were used for statistical analysis.

# CHAPTER 4

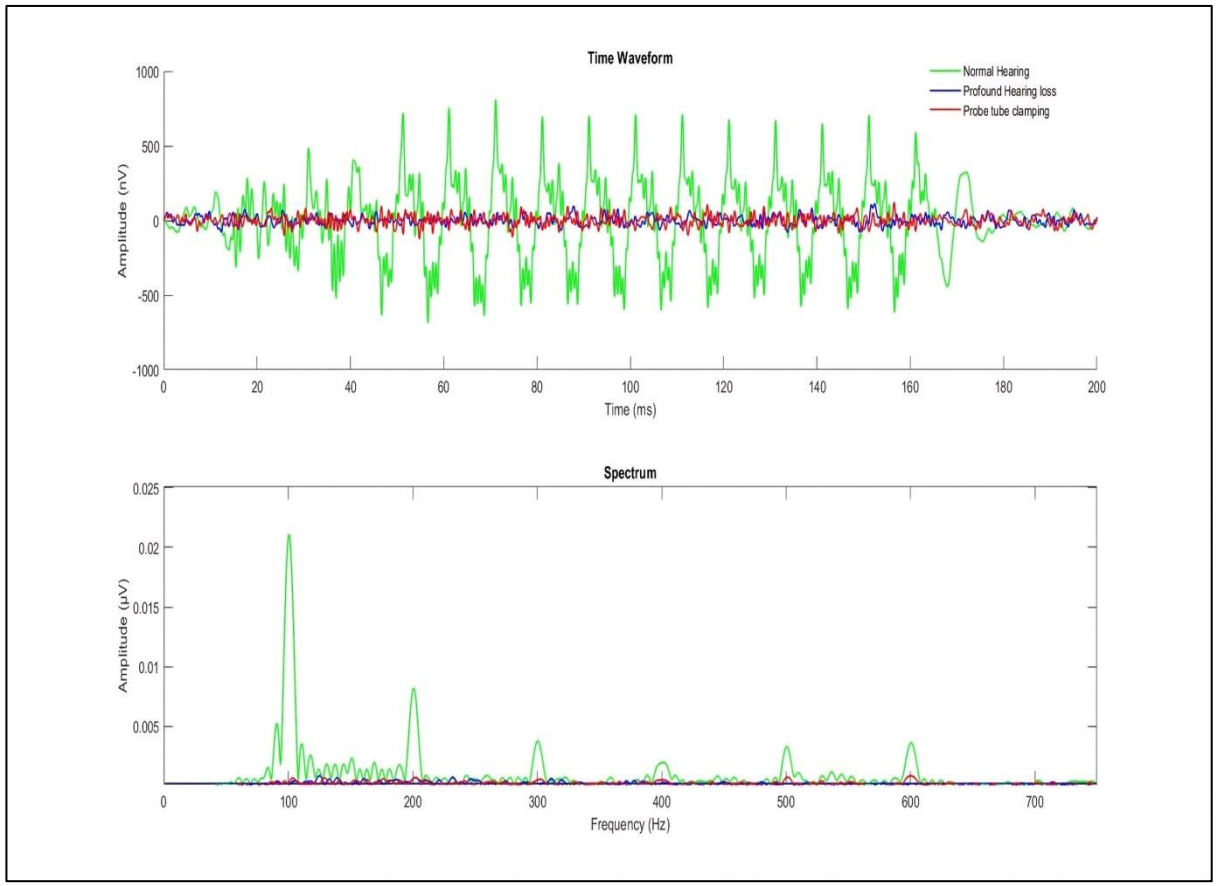
# RESULTS

The current study examined the effect of contralateral acoustic stimulation on frequency-following responses to speech and complex tone. Prior to the commencement of the experiments, the presence of true neural responses was ensured using two control procedures. To verify the source of the recorded activity, the probe tube was first clamped during recording. Because clamping prevents the stimulus from being heard, genuine neural activity should produce no responses. Therefore, any responses that persist while the tube is clamped are likely due to stimulus artifact rather than a neural response. Second, control recordings were obtained from a participant with profound hearing loss to confirm that no neural response was present under these conditions.

Figure 4.1 displays the responses obtained from a normal-hearing participant, both with and without probe tube clamping, as well as from a participant with profound hearing loss. As depicted, no responses were observed during the clamped tube condition or in the individual with profound hearing loss. Combined with the use of electrically shielded earphones, these procedures verified that the recordings in the main experiment were physiological in nature and free from stimulus artifact contamination. Having successfully ruled out stimulus artifacts, the subsequent experiments were then carried out.

**Figure 4.1**

*Waveform and spectrum of responses recorded in normal hearing (in probe tube clamping conditions), and profound hearing loss.*




Shapiro-Wilk's test was conducted to assess the normality of all variables. Results indicated that the data significantly deviated from a normal distribution ($W < 0.90$, $p < .05$). Therefore, non-parametric tests were employed for subsequent inferential analyses.

**Objective 1. To compare the spectral amplitude of $FFR_{ENV}$ and $FFR_{TFS}$ in the presence and absence of contralateral acoustic stimulus (CAS) for:**

a. Original /ba/ syllable

b. 300 Hz high-pass filtered /ba/ syllable.

***Effect of CAS on Envelope Following Responses ($FFR_{ENV}$) for the /ba/ Syllable***

This part of the result addresses objective 1. Figure 4.2 shows median, quartile deviation and individual data points of $FFR_{ENV}$ amplitudes with and without CAS. From the Figure it can be seen that addition of CAS did not alter the $FFR_{ENV}$ amplitudes. Figures 4.3 (a) and (b) shows the grand average waveform and spectrum of /ba/ with and without CAS

**Figure 4.2**

*Median, quartile deviation and individual data points of amplitude of* $FFR_{ENV}$ *for /ba/ with and without CAS.*

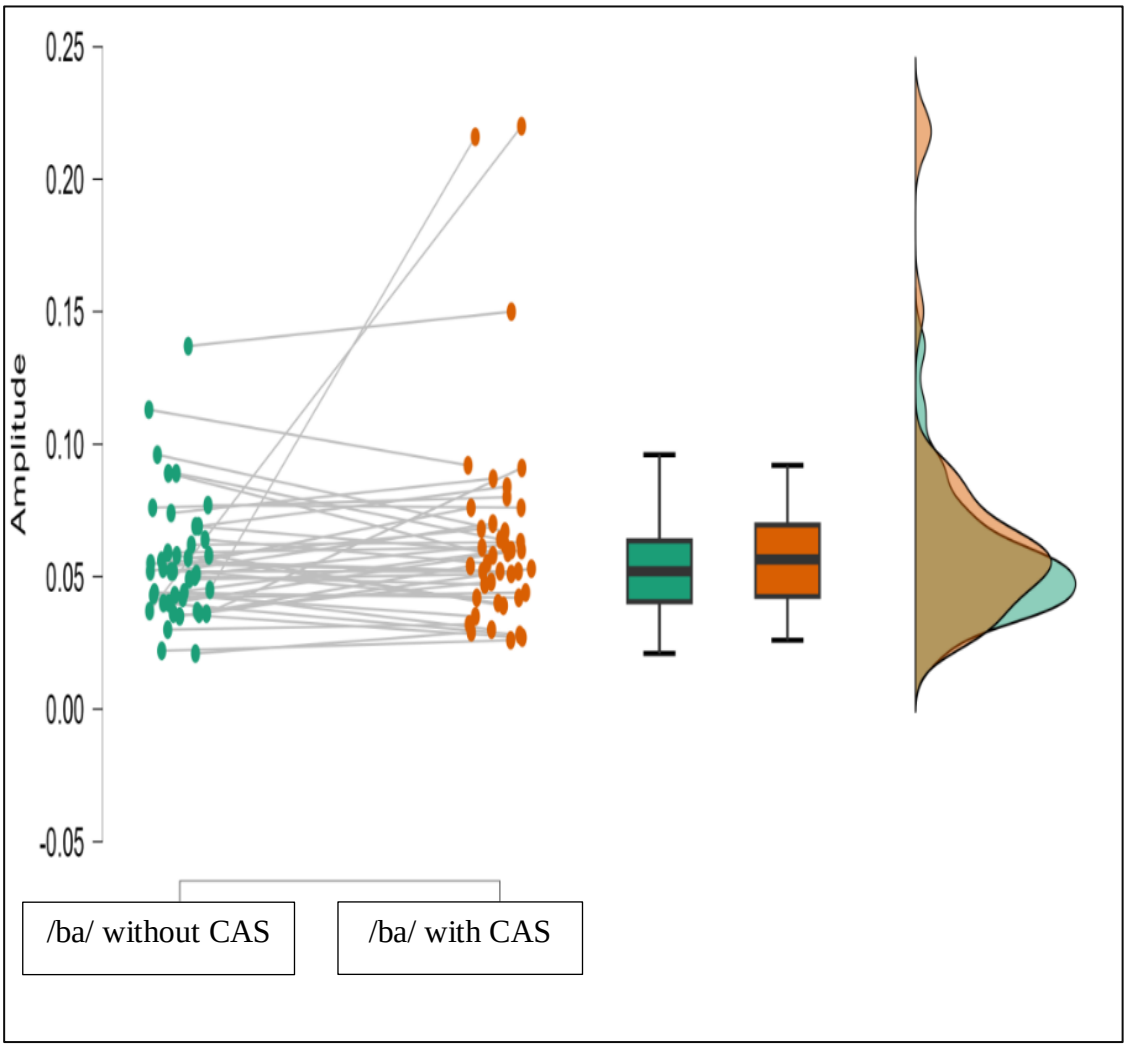
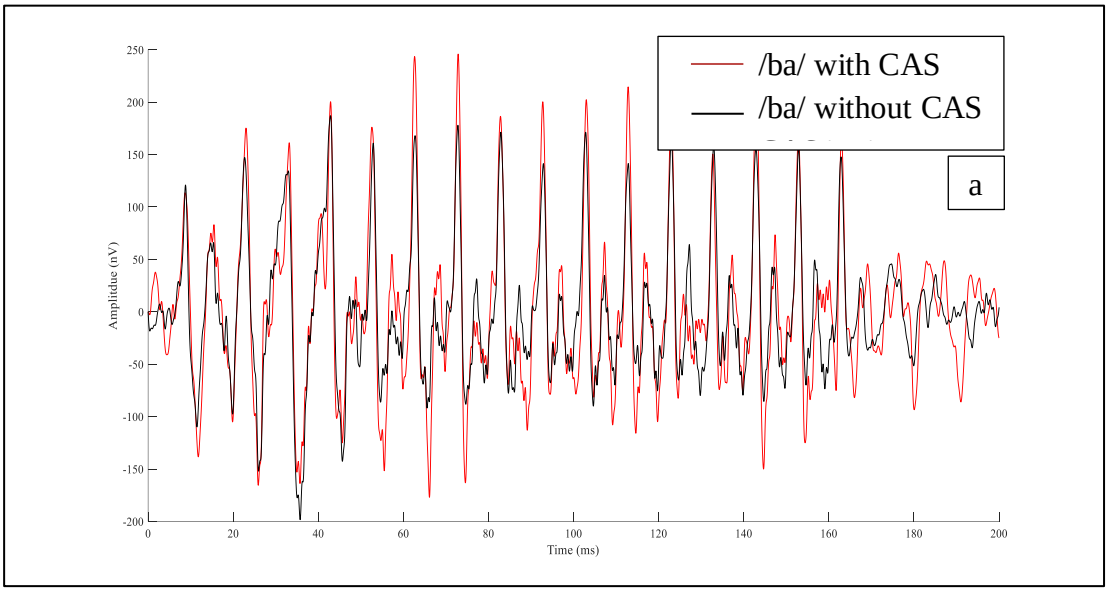
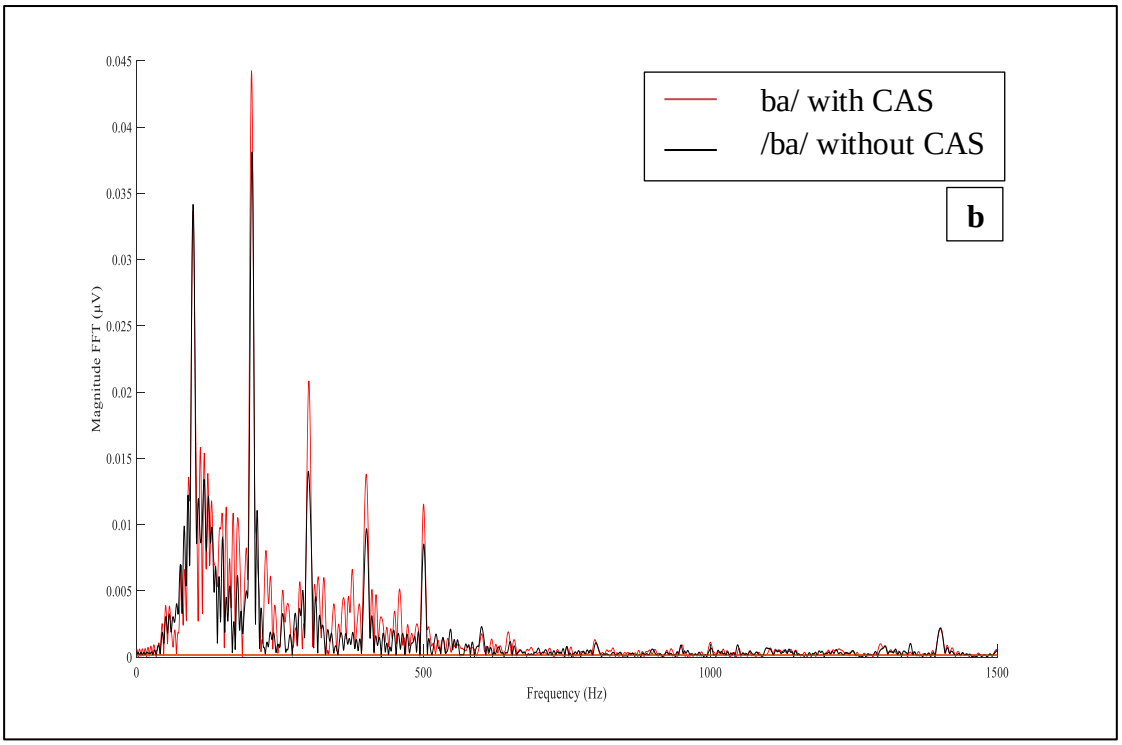


**Figure 4.3**

*Waveform (a) and spectrum (b) of* $FFR_{ENV}$ amplitude in response to /ba/ with (red) and without *CAS (black).*



A Wilcoxon signed-rank test was conducted to evaluate the effect of CAS on $FFR_{ENV}$ amplitudes—specifically the fundamental frequency (F0)—in response to the /ba/ syllable. The analysis revealed no statistically significant difference in F0 amplitudes between the two conditions, ($W = 366.00$, $z = 0.84$, $p = .407$, $r = .09$).

Visual inspection of the data distribution, as depicted in the raincloud plot (see Figure 4.2), corroborates these statistical findings. The boxplots for both conditions demonstrate substantial overlap with nearly identical median values, reflecting no meaningful shift in central tendency. Furthermore, the probability density curves (half-violin plots) indicate that the overall spread and density of the $FFR_{ENV}$ amplitudes remained largely unchanged following the introduction of CAS.

The grand average waveforms in (see Figure 4.3) (a) showed considerable overlap between the with CAS and without CAS conditions across the entire response window, indicating that amplitude characteristics remained largely unchanged between the two conditions. The grand average spectrum in (b) further reinforced this pattern, as the spectral energy appeared broadly consistent across frequencies, with peaks at the fundamental frequency and harmonic components maintaining a similar distribution regardless of whether CAS was present or absent.

### *Effect of CAS on Envelope-Following Responses $FFR_{ENV}$ for the Modified /ba/ Syllable*

This section addresses the second part of the first objective, which was to assess the effect of with and without CAS on /ba/ with missing F0. The Figure 4.4 shows median, quartile deviation and individual data points of $FFR_{ENV}$ amplitudes with and without CAS. Figures 4.5 (a) and (b) shows the grand average waveform and spectrum of /ba/ with missing F0 with and without CAS.

**Figure 4.4**

*Median, quartile deviation and individual data points of amplitude of* $FFR_{ENV}$ *for /ba/ with missing F0 with and without CAS.*

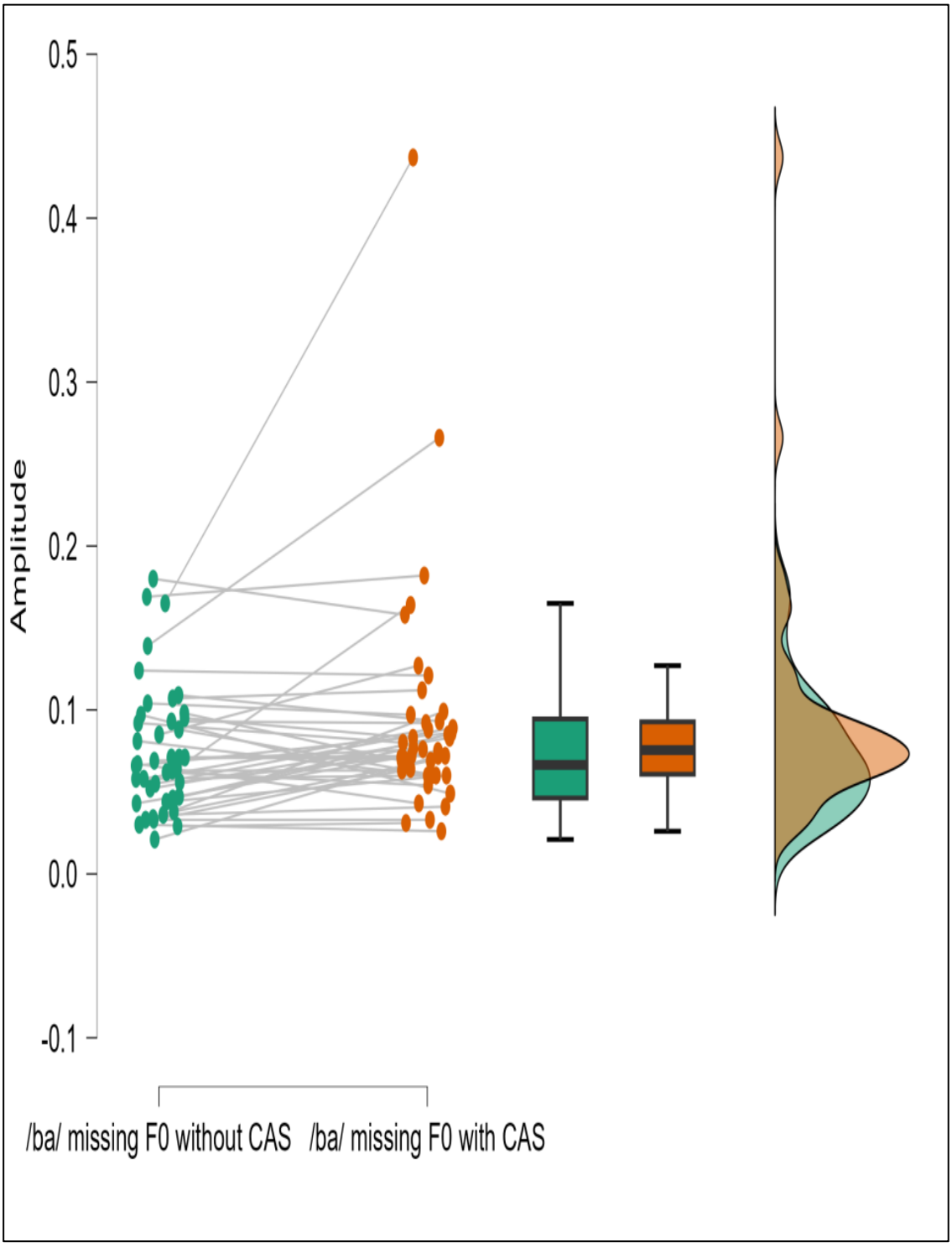
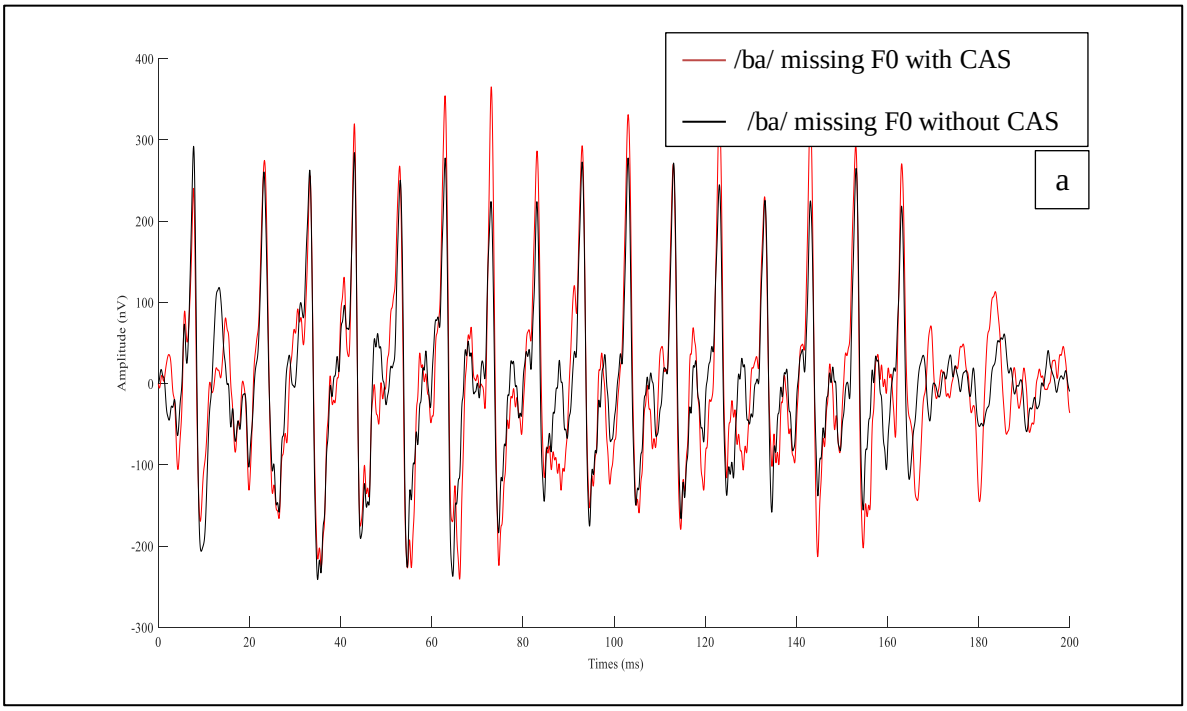
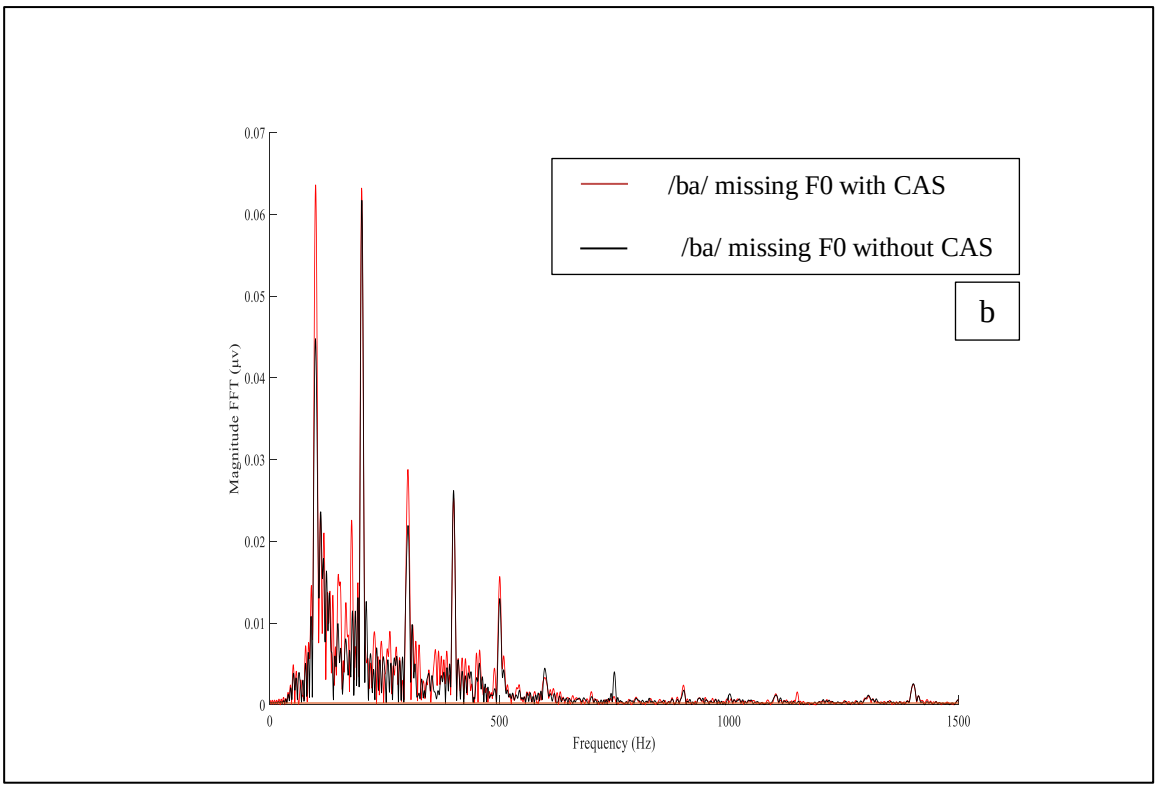


**Figure 4.5**

*Waveform (a) and spectrum (b) of $FFR_{ENV}$ amplitude in response to /ba/ with missing F0 with (red) and without (black) CAS.*



To test the statistical significance of the difference in the $FFR_{ENV}$ amplitudes, we conducted a Wilcoxon signed-rank test. The results showed that the CAS significantly increased the amplitudes of $FFR_{ENV}$ ($W = 227.50$, $z = -2.27$, $p = .024$, $r = .42$). Introducing the CAS had a moderate effect on the $FFR_{ENV}$ amplitude.

The grand average waveforms in Figure 4.5 (a) shows visible separation between the with CAS and without CAS traces at multiple points across the response window, indicating that CAS enhanced the amplitude encoding of /ba/ with missing F0. The grand average spectrum in (b) reflected a similar trend in the spectral domain, where differences in energy distribution were apparent between the two conditions, particularly across the lower harmonic regions.

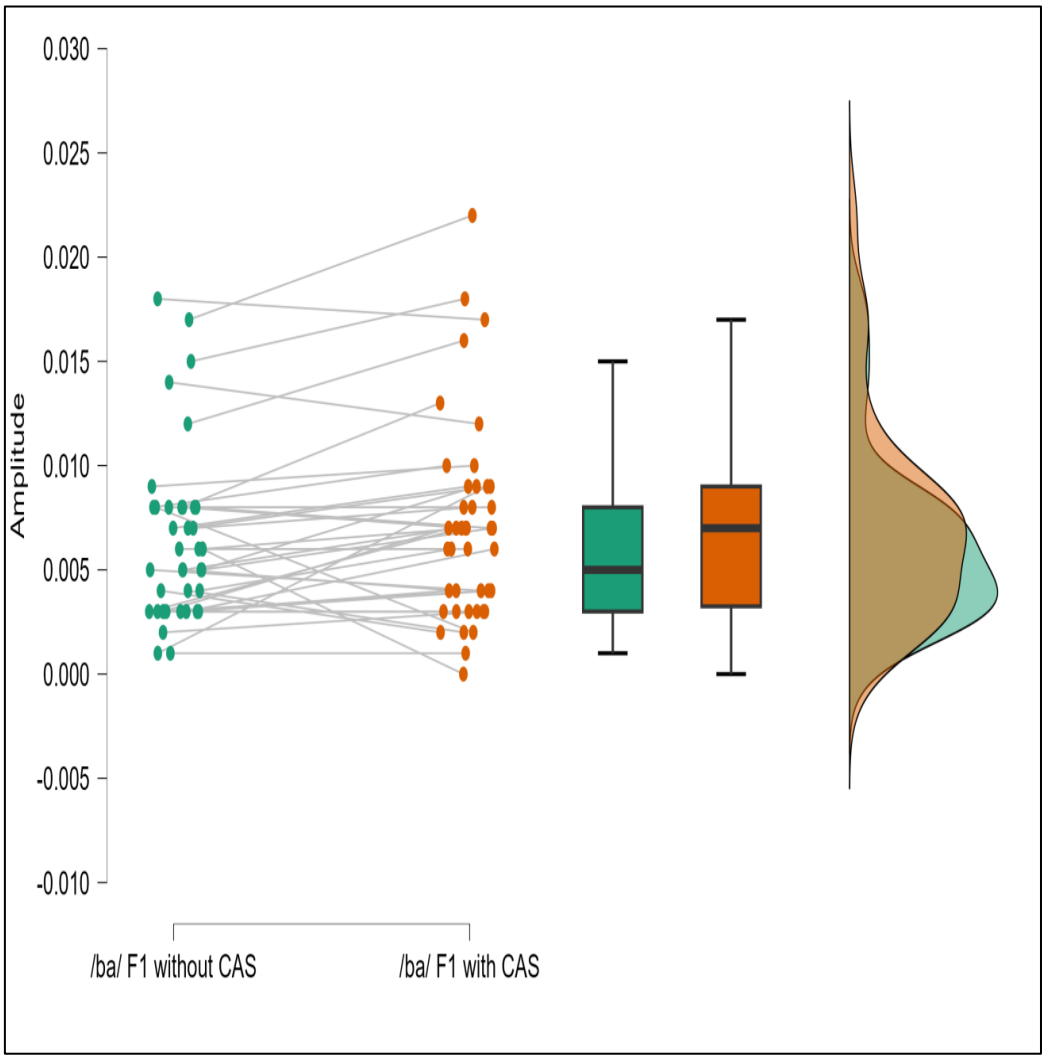
### *Effect of CAS on $FFR_{TFS}$ for the Original /ba/ Syllable*

This section addresses the study's first objective. We examined the effect of CAS on the spectral amplitude of the $FFR_{TFS}$ for original /ba/. Specifically, we assessed fine structure by extracting and comparing the amplitudes at both the first (F1) and second (F2) formants.

**F1 Amplitude.** The Figure 4.6 shows median, quartile deviation and individual data points of $FFR_{TFS}$ amplitudes with and without CAS. Figure 4.8 (a) and (b) shows the grand average $FFR_{TFS}$ waveform and spectrum. To assess the statistical significance of the effect of CAS we ran a Wilcoxon signed-rank. Results showed a significantly higher amplitudes of $FFR_{TFS}$ when CAS was present ($W = 142.00$, $z = -2.28$, $p = .022$, $r = .46$, $SE = 0.20$). The CAS yielded a moderate effect, as reflected by a rank-biserial correlation.

**Figure 4.6**

*Median, quartile deviation and individual data points of amplitude of* $FFR_{TFS}$ for */ba/ F1 with and without CAS.*

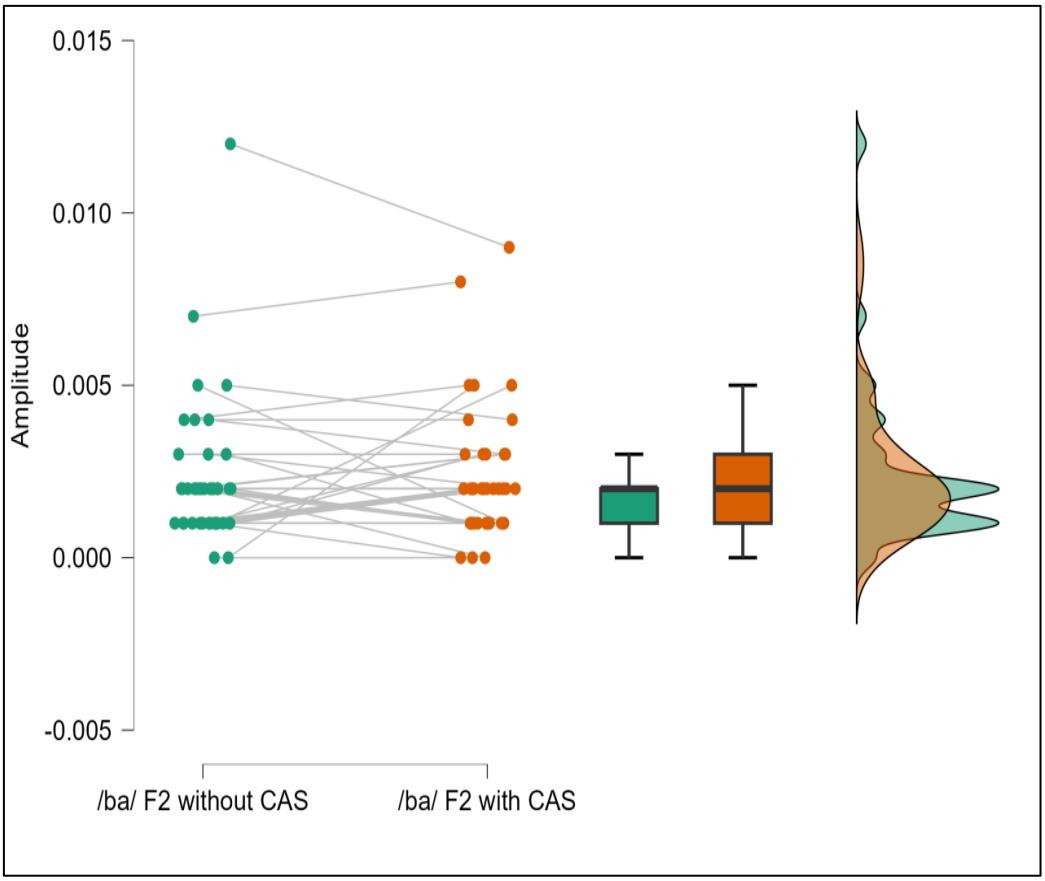



The grand average waveform in Figure 4.8 (a) revealed noticeable amplitude differences between the with CAS and without CAS conditions at several points throughout the response window. The with CAS trace appearing relatively elevated, suggesting that CAS enhanced the amplitude of /ba/. The grand average spectrum in (b) similarly reflected this enhancement, with CAS condition showing comparatively higher spectral energy in the F1 regions.

**F2 Amplitude.** The Figure 4.7 shows median, quartile deviation and individual data points of $FFR_{TFS}$ amplitudes with and without CAS. Figure 4.8 (a) and (b) shows the grand average $FFR_{TFS}$ waveform and spectrum.

**Figure 4.7**

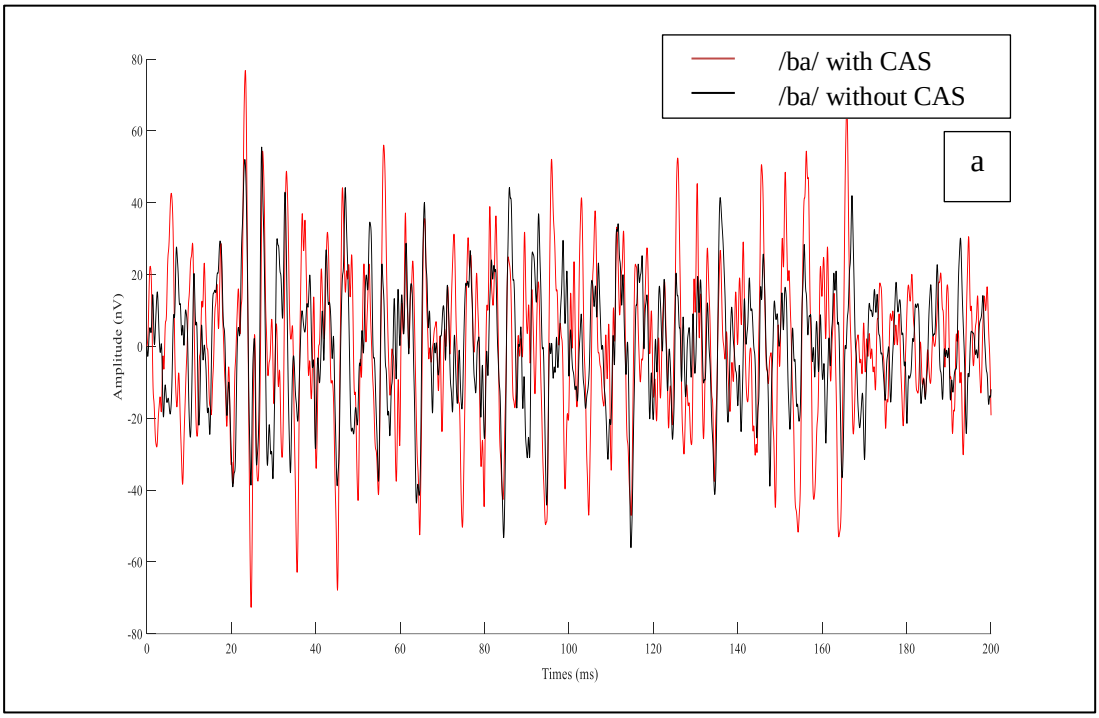
*Median, quartile deviation and individual data points of amplitude of* $FFR_{TFS}$ *for /ba/ F2 with and without CAS.*

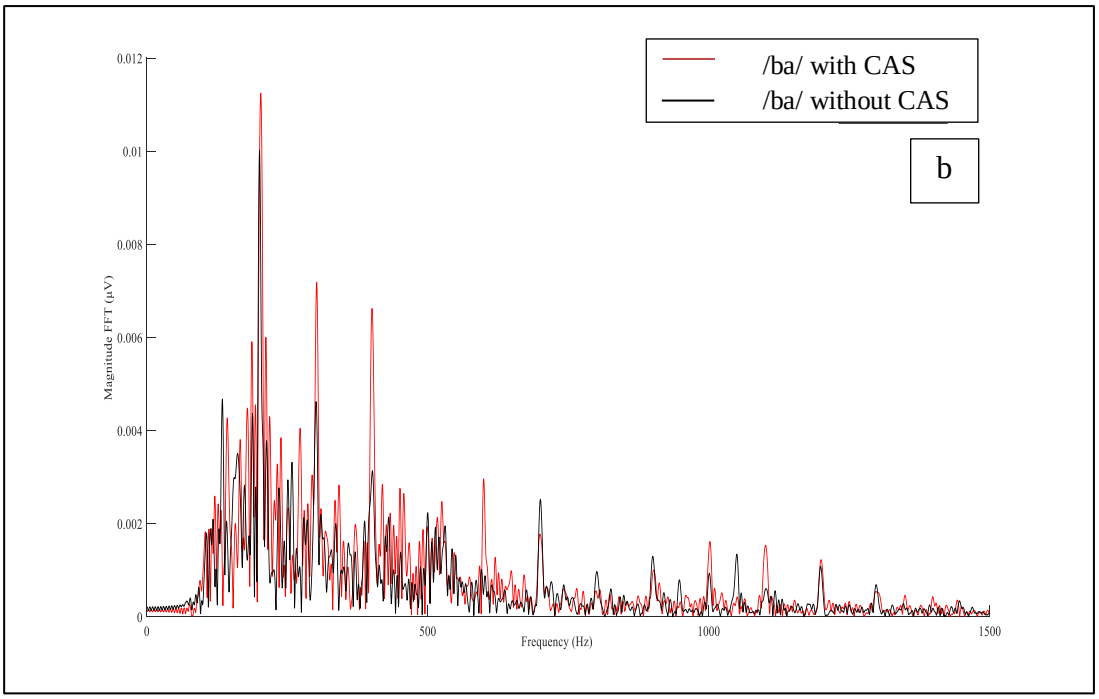



Wilcoxon signed-rank test showed that CAS did not lead to a statistically significant change in F2 amplitudes, ($W$ = 182.50, $z$ = 0.16, $p$ = .880). The calculated effect size was negligible suggesting that the CAS essentially had no impact on the neural encoding of the second formant. The boxplots overlap heavily, and the trajectories of individual data points demonstrate minimal movement between the with and without CAS conditions.

**Figure 4.8**

*Waveform (a) and spectrum (b) of $FFR_{TFS}$ amplitude in response to /ba/ with (red) and without (black) CAS.*



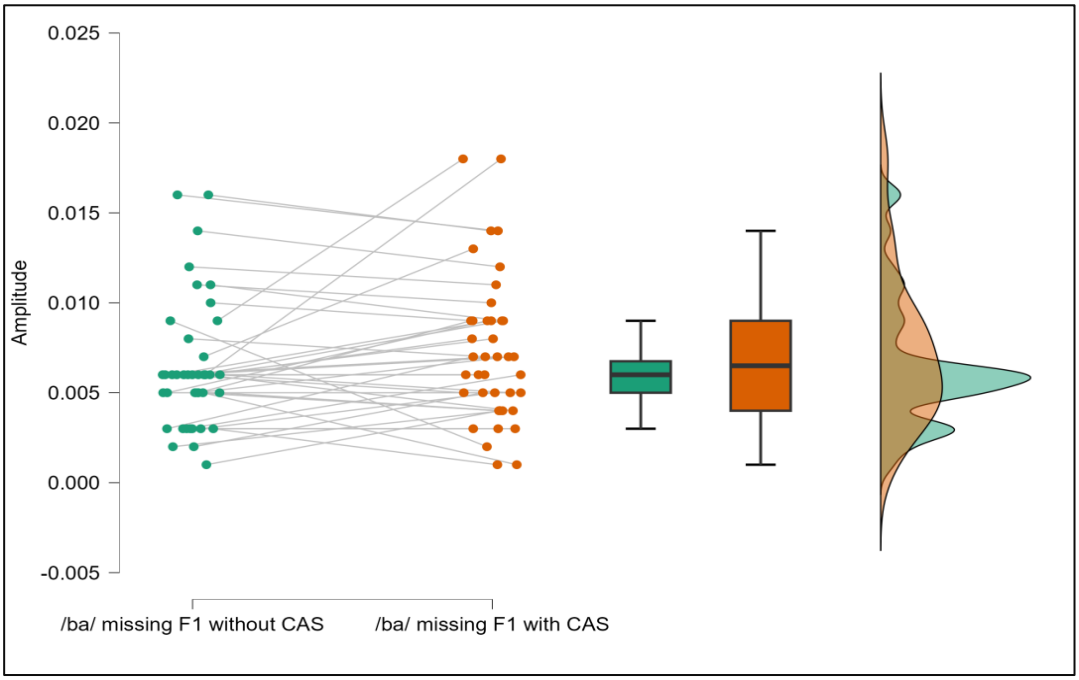
### *Effect of CAS on $FFR_{TFS}$ for the Modified /ba/ Syllable*

This section addresses the study's first objective. We examined the effect of CAS on the spectral amplitude of the $FFR_{TFS}$ for /ba/ with missing fundamental. Specifically, we assessed fine structure by extracting and comparing the amplitudes at both the F1 and F2 between with CAS and without CAS conditions.

**F1 Amplitude.** The Figure 4.9 shows median, quartile deviation and individual data points of $FFR_{TFS}$ amplitudes with and without CAS. From the Figure it can be seen that addition of CAS did not alter the $FFR_{TFS}$ amplitudes. Figures 4.11 (a) and (b) shows grand average waveform and spectrum of /ba/ missing with and without CAS.

**Figure 4.9**

*Median, quartile deviation and individual data points of amplitude of* $FFR_{TFS}$ for */ba/ missing F1 with and without CAS.*

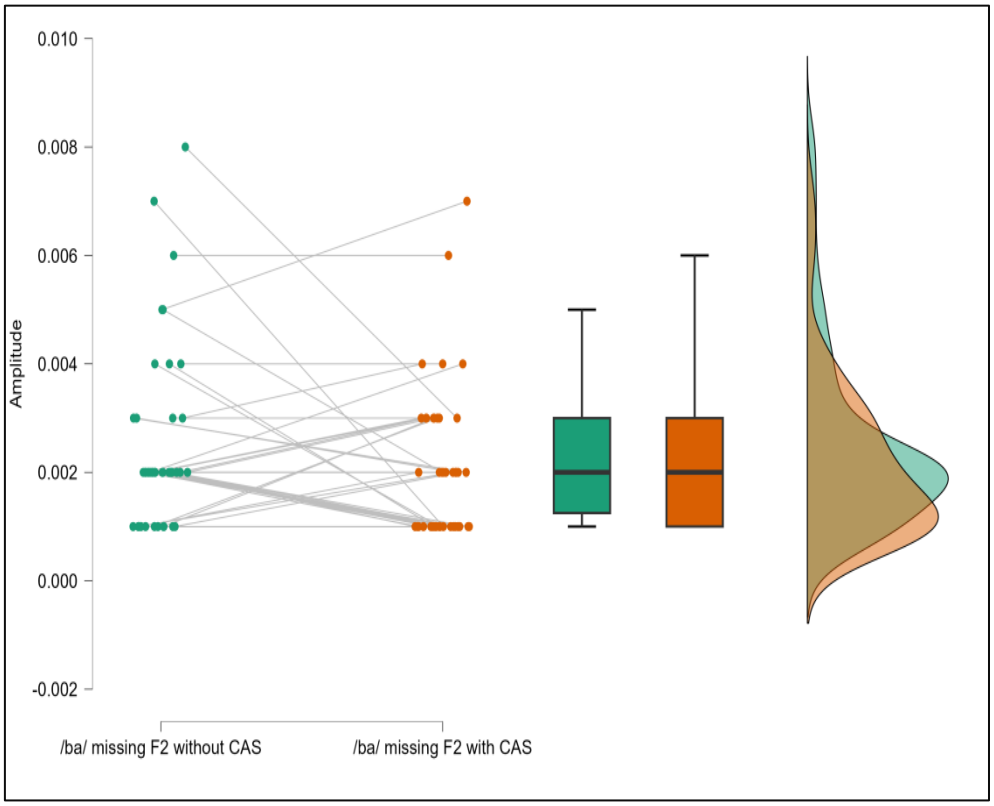


Wilcoxon signed-rank test indicated no statistically significant difference in F1 amplitude between with and without CAS conditions ($W = 220.50$, $z = -1.54$, $p = .122$). A quick look at the data distribution in Figure 4.9 visually reinforces this statistical outcome. The boxplots for the with CAS and without CAS conditions overlap heavily, and their median values are close to one another. When you follow the lines connecting the individual paired data points, you can see a highly mixed response among the participants. While some individuals showed an increase in amplitude when the CAS was introduced, others showed decreases or remained entirely stable. Because of this variability, the probability density curves on the right show no major, unified shift in the overall data.

**F2 Amplitude.** The Figure 4.10 shows median, quartile deviation and individual data points of $FFR_{TFS}$ amplitudes with and without CAS. From the Figure it can be seen that addition of CAS did not alter the $FFR_{TFS}$ amplitudes. Figures 4.11 (a) and (b) shows grand average waveform and spectrum of /ba/ missing with and without CAS.

**Figure 4.10**

*Median, quartile deviation and individual data points of amplitude of* $FFR_{TFS}$ for */ba/ missing F2 with and without CAS.*

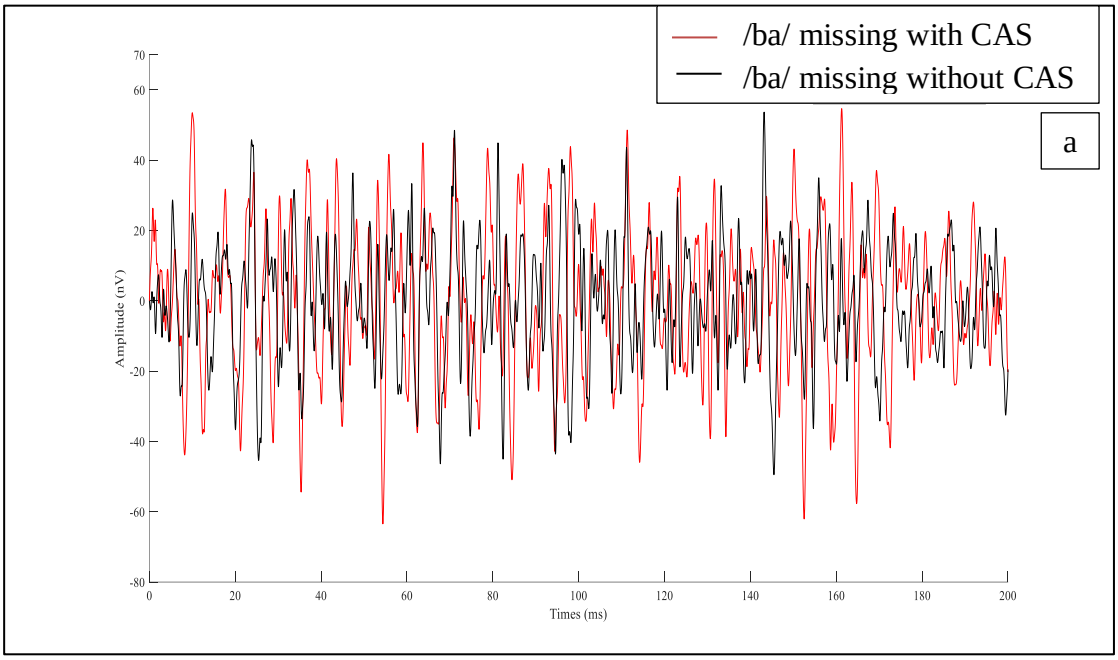


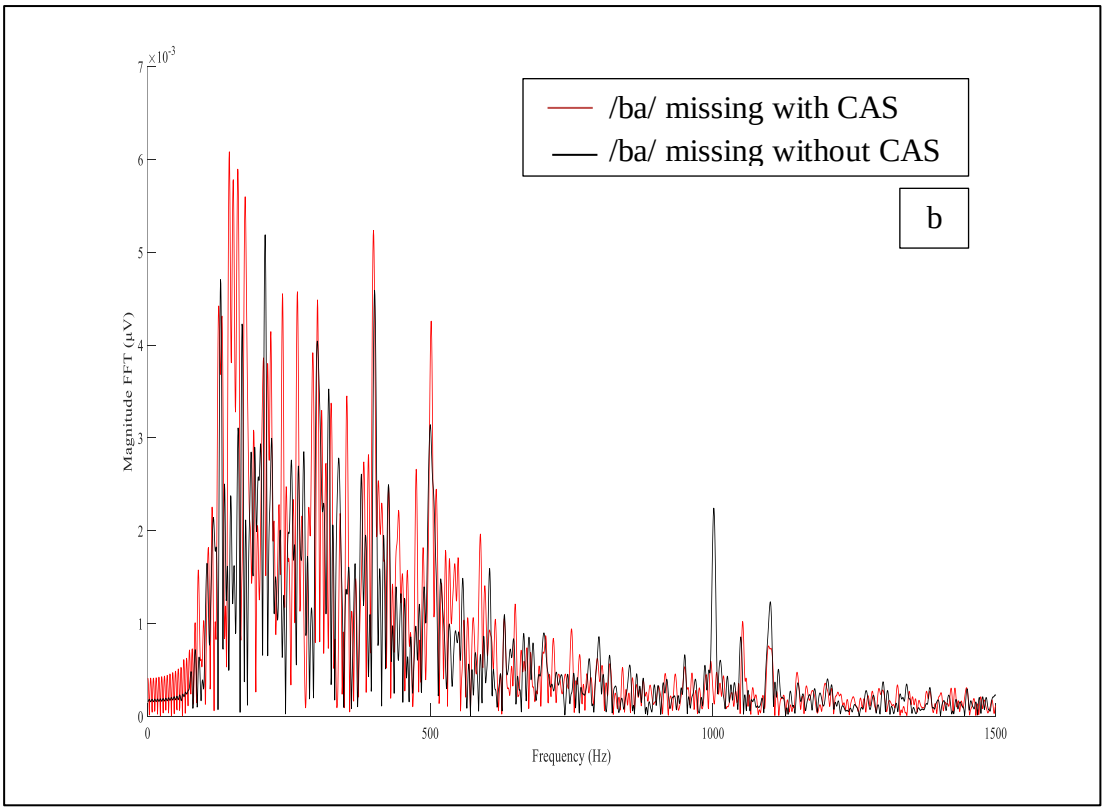

Wilcoxon signed-rank test confirmed that applying the CAS had no statistically significant impact on F2 amplitudes, ($W$ = 261.00, $z$ = 0.94, $p$ = .333). The calculated effect size was quite small suggesting the noise had little to no meaningful influence on this specific measure.

The visualization for the F2 data (see Figure 4.10) perfectly mirrors this lack of significance. The overall density curves are nearly identical across both testing environments, and the individual trajectories cross back and forth without demonstrating any cohesive upward or downward trend.

**Figure 4.11**

*Waveform (a) and spectrum (b) of $FFR_{TFS}$ amplitude in response to /ba/ missing F0 with (red) and without (black) CAS.*



The grand average waveform in Figure 4.11 (a) indicated a marginal amplitude increment in the with CAS condition compared to a relative decrement observed in the without CAS condition at certain points across the response window, though both traces remained largely overlapping overall. The grand average spectrum in (b) mirrored this pattern, with the with CAS condition reflecting slightly higher spectral energy at certain harmonic regions, while the without CAS condition showed comparatively reduced energy across those same frequency areas.

**Objective 2. To compare the spectral amplitude of $FFR_{ENV}$ elicited by original /ba/ and 300 Hz high-pass filtered /ba/**

The objective aimed to determine if the neural encoding of the envelope represented by the spectral amplitude of $FFR_{ENV}$ differed significantly when the physical fundamental frequency F0 was removed from the stimulus. The Figure 4.12 shows median, quartile deviation and individual data points of $FFR_{ENV}$ amplitudes for original /ba/ versus 300 Hz high-pass filtered /ba/. Figures 4.13 (a) and (b) shows grand average waveform and spectrum of /ba/ and /ba/ with missing F0.

**Figure 4.12**

*Median, quartile deviation and individual data points of amplitude of* $FFR_{ENV}$ *for /ba/ and /ba/ with missing F0.*

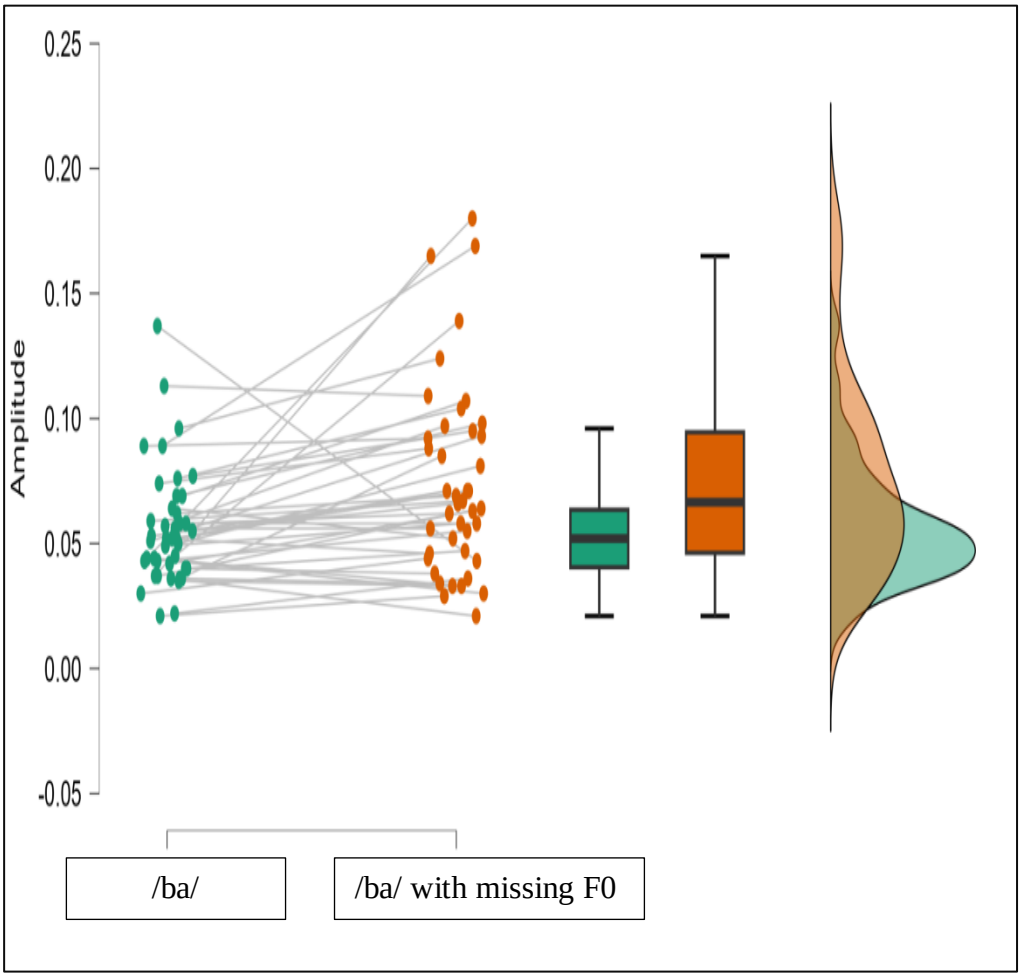
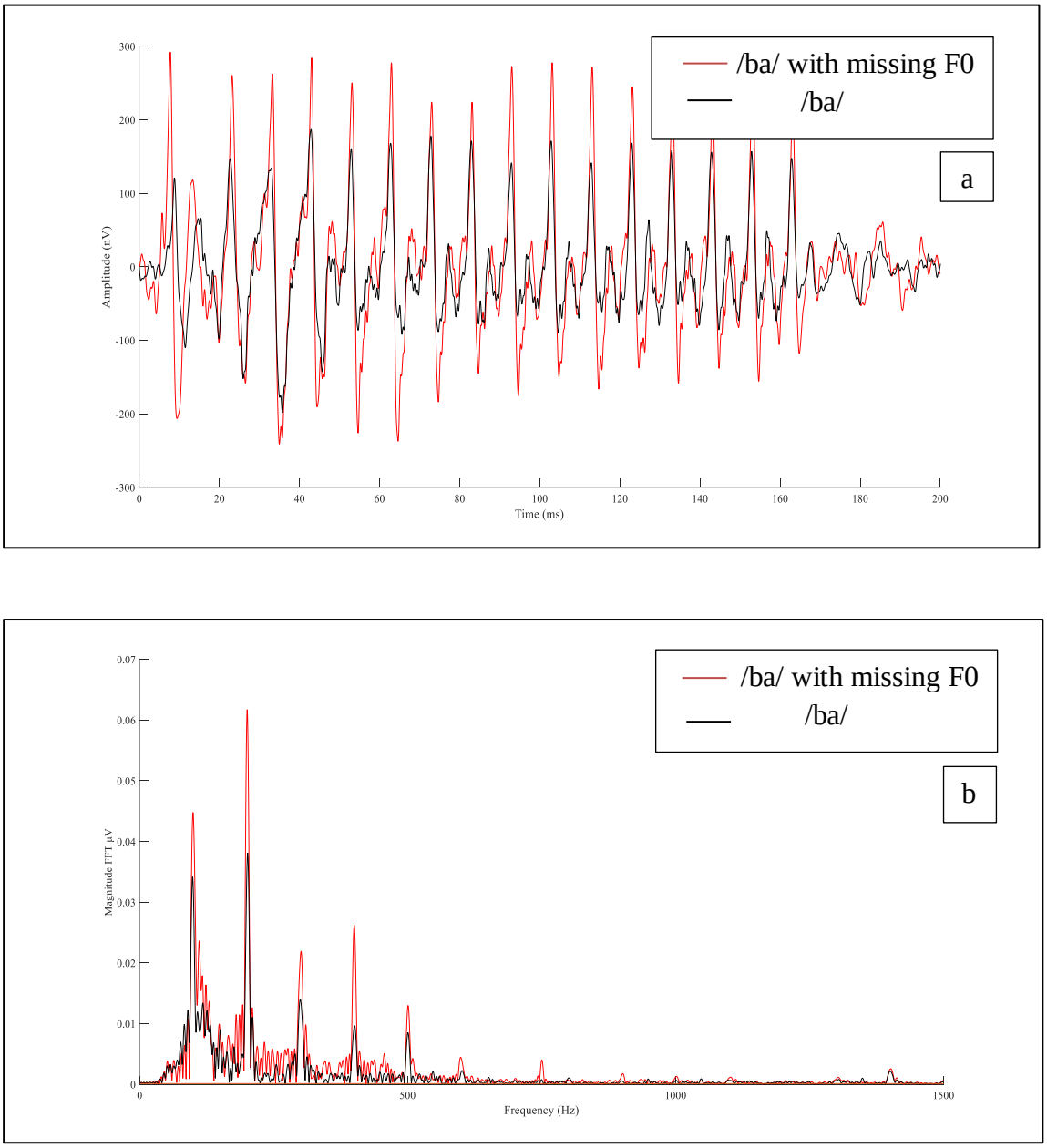


**Figure 4.13**

*Waveform (a) and spectrum (b) of $FFR_{ENV}$ amplitude in response to /ba/ (black) and /ba/ missing F0 (red).*




A Wilcoxon signed-rank test was conducted to compare $FFR_{ENV}$ amplitudes between the original /ba/ and /ba/ with missing fundamental. The statistical analysis revealed a significant difference between the two conditions ($W = 124.50$, $z = -3.84$, $p < .001$, $r = .70$)

As illustrated in the raincloud plot and boxplots, the spectral amplitude of $FFR_{ENV}$ was significantly higher for the /ba/ with missing F0. The effect size, calculated using the Rank-Biserial Correlation, was large indicating a robust reduction in neural encoding strength when the F0 was physically absent.

The grand average waveform in Figure 4.13 (a) showed a clear amplitude increment in the /ba/ missing F0 without CAS condition, with notably higher peaks and deeper troughs compared to the /ba/ without CAS condition, suggesting stronger envelope encoding for the missing F0 stimulus. The grand average spectrum in (b) mirrored this pattern, where the /ba/ missing F0 without CAS condition exhibited markedly higher spectral energy across the lower harmonic regions, while the /ba/ without CAS condition showed a relative decrement in energy across those same areas.

**Objective 3. To compare the spectral amplitude of $FFR_{ENV}$, in the presence and absence of CAS for**

a. Complex tone with 260 Hz $F_0$
b. Complex tone with 260 Hz $F_0$ excluding the first two harmonics

Figure 4.14 shows median, quartile deviation and individual data points of $FFR_{ENV}$ amplitudes with and without CAS. From the Figure, it can be seen that the addition of CAS alters the $FFR_{ENV}$ amplitudes. Figures 4.15 (a) and (b) shows the grand average waveform and spectrum of complex tone.

**Figure 4.14**

*Median, quartile deviation and individual data points of amplitude of* $FFR_{ENV}$ for *complex tone with and without CAS.*

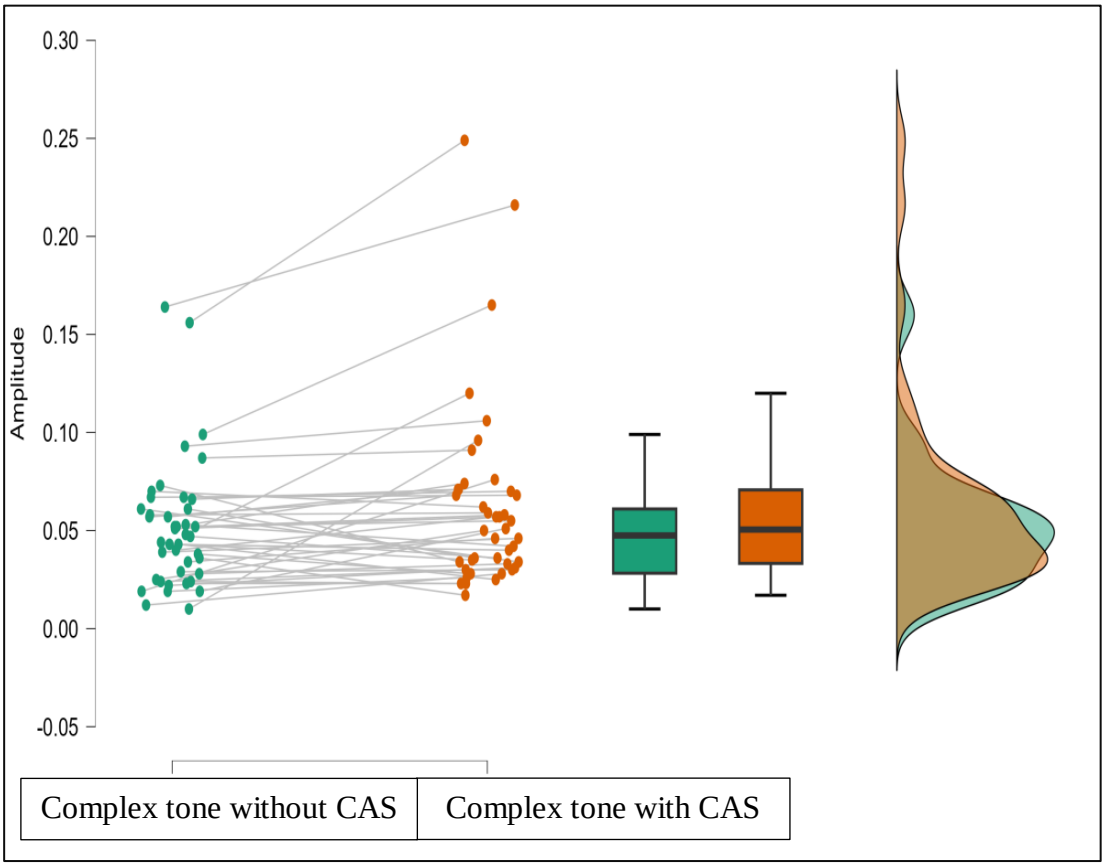
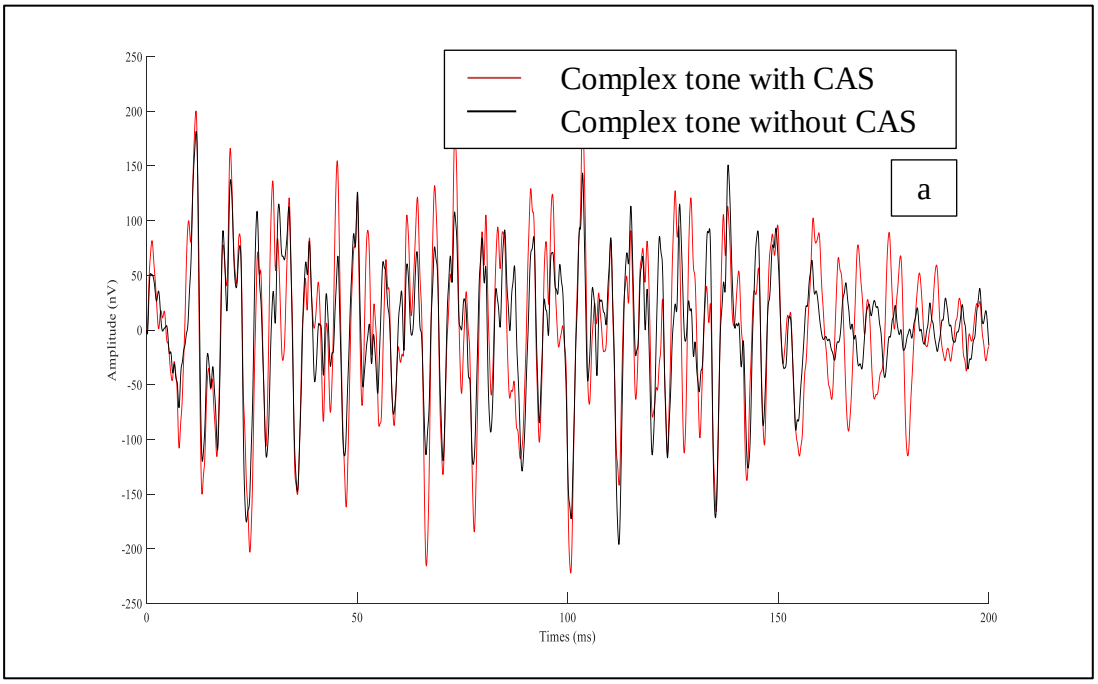
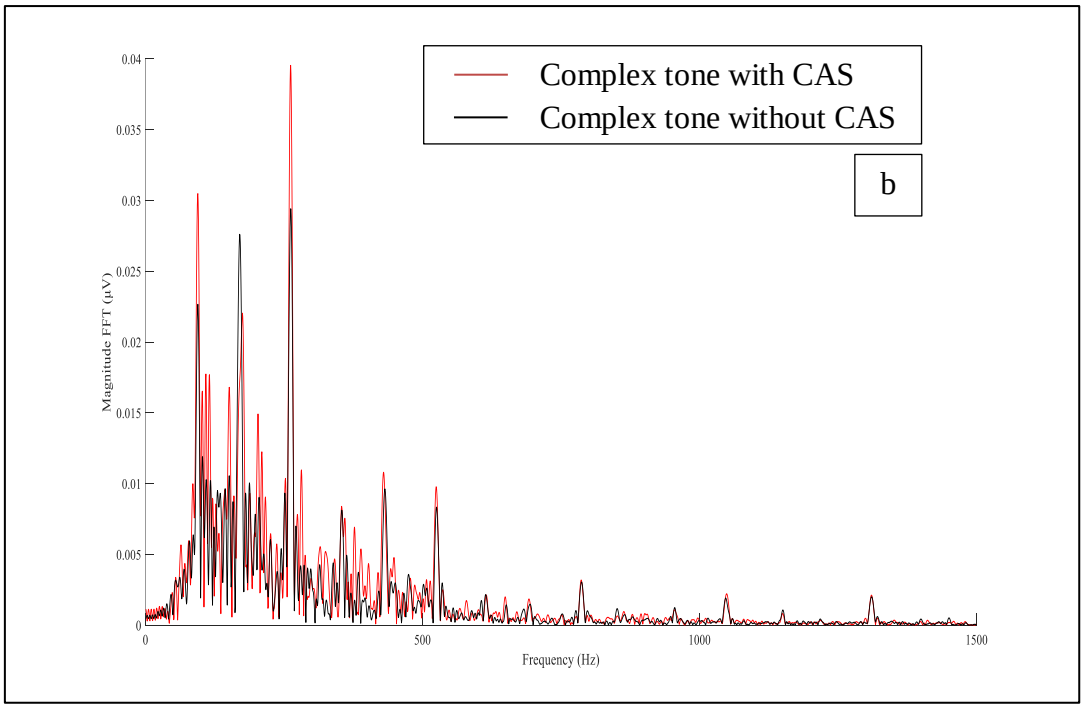


**Figure 4.15**

*Waveform (a) and spectrum (b) of $FFR_{ENV}$ amplitude in response to complex tone with (red) and without (black) CAS.*



To test this, we compared the complex tone amplitudes with CAS and without CAS condition. When we ran a Wilcoxon signed-rank test on these paired samples, the results showed a statistically significant difference between the two listening environments ($W$ = 259.50, $z$ = −2.22, $p$ = .027, $r$ = .40, $SE$ = 0.18). The introduction of CAS had a moderate increment in the amplitude of the complex tone.

The data spread in the raincloud plot (see Figure 4.9) helps visualize this statistical shift. The boxplots highlight a noticeable change in both the median amplitude and the interquartile range once the CAS was turned on. By tracing the lines connecting the paired individual data points, it becomes clear that a substantial number of participants experienced a distinct shift in their F0 amplitudes with CAS. Furthermore, the probability density curves on the right side of the plot back this up by displaying an altered, slightly broader overall distribution of the responses during CAS.

The grand average waveform in Figure 4.15 (a) revealed an amplitude increment with CAS condition compared to a relative decrement in the without CAS condition at several points across the response window. The grand average spectrum in (b) mirrored this pattern, with CAS condition showing higher spectral energy at certain harmonic peaks compared to the without CAS condition.

***Effect of CAS on Envelope-Following Responses $FFR_{ENV}$ for the Modified Complex Tone***

To address the second part of our third objective, we explored how CAS affects the $FFR_{ENV}$ when listeners are presented with a modified complex tone. For this specific condition, the stimulus had a 260 Hz F0 , but the first two harmonics were explicitly excluded. Our goal was to see if the brainstem's encoding of the F0 remained stable or shifted under these altered conditions. The Figure 4.16 shows median, quartile deviation and

individual data points of $FFR_{ENV}$ amplitudes with and without CAS. From the Figure it can be seen that addition of CAS alter the $FFR_{ENV}$ amplitudes. Figures 4.17 (a) and (b) shows the grand average waveform and spectrum of complex tone with missing F0 signal.

**Figure 4.16**

*Median, quartile deviation and individual data points of amplitude of* $FFR_{ENV}$ for complex tone *with missing F0 with and without CAS.*

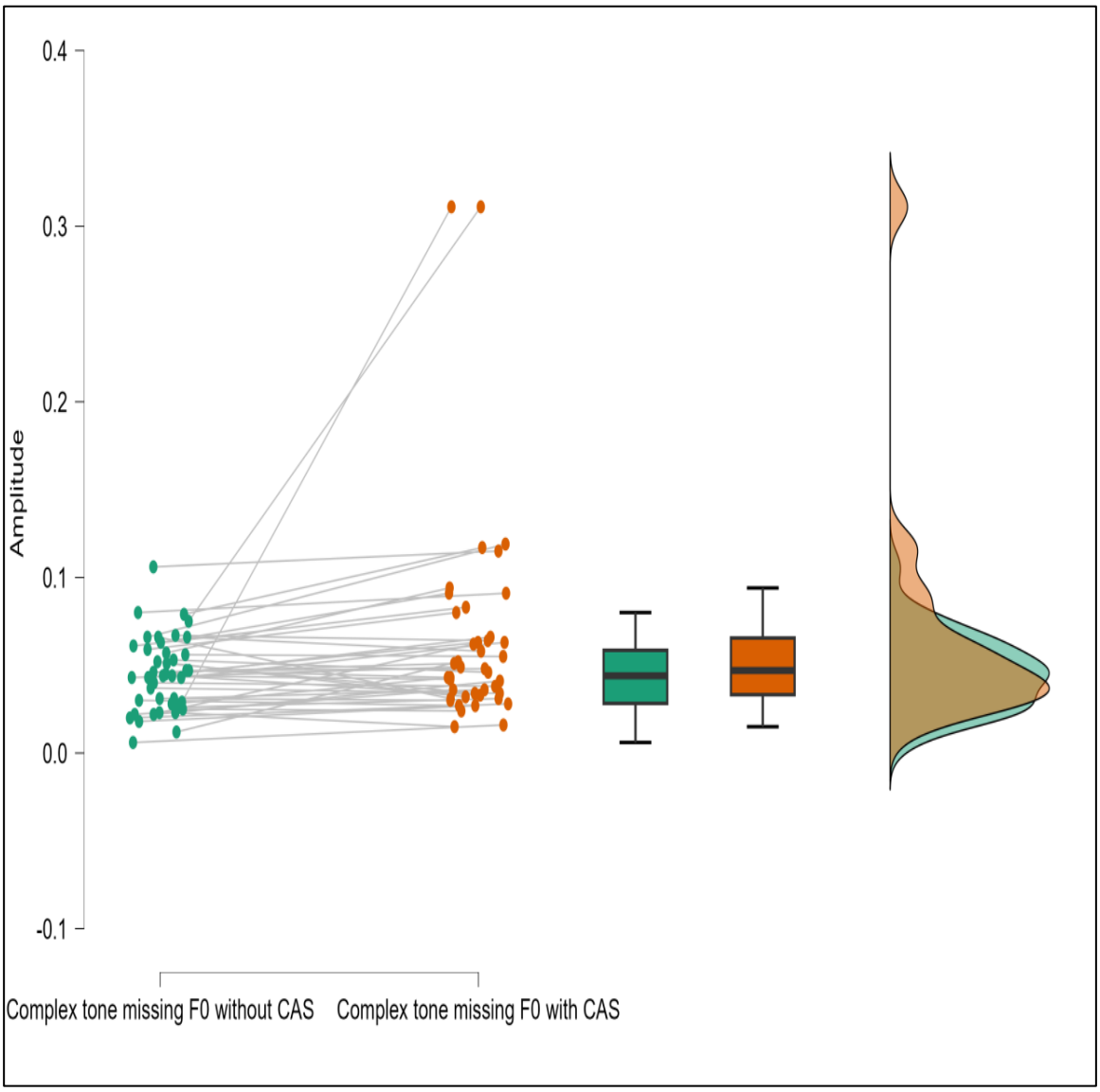
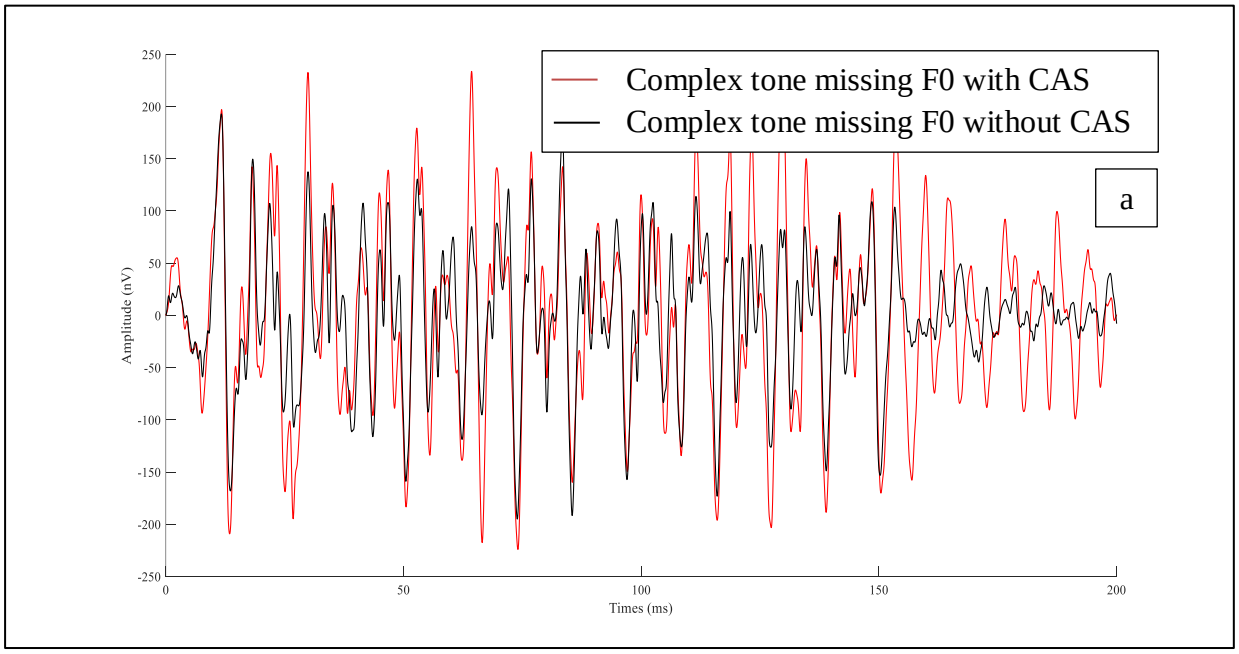
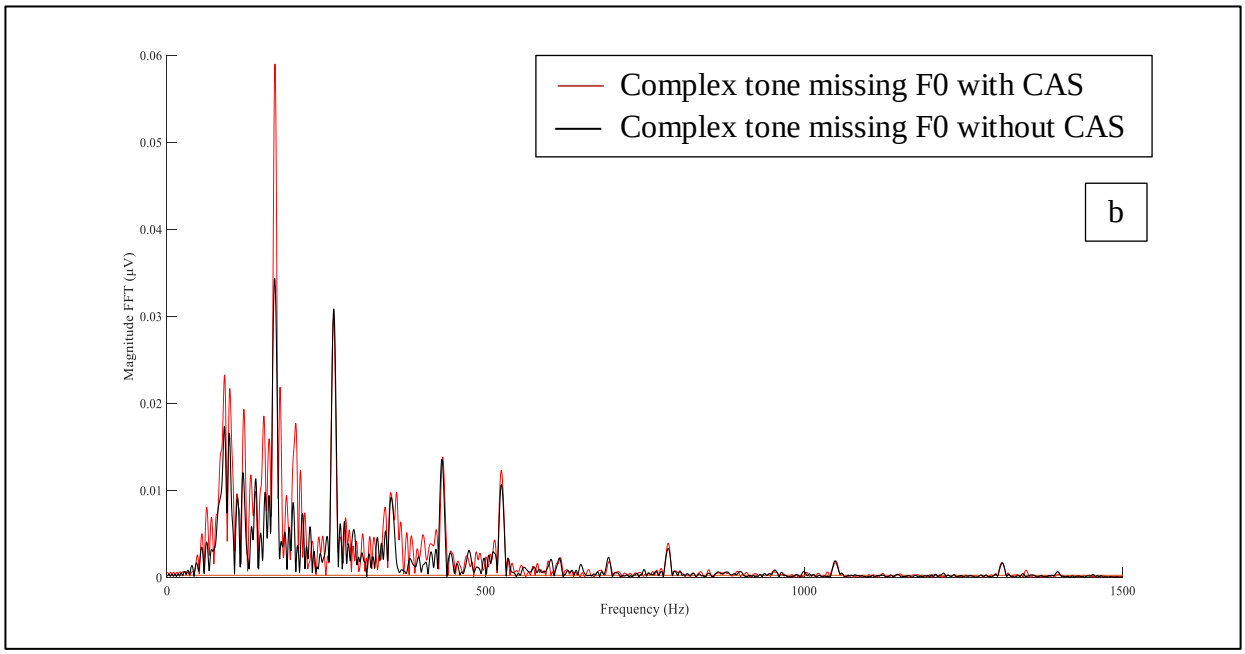


**Figure 4.17**

*Waveform (a) and spectrum (b) of $FFR_{ENV}$ amplitude in response to complex tone with missing F0 with (red) and without (black) CAS.*



When we evaluated the data, a Wilcoxon signed-rank test revealed a statistically significant difference between the $FFR_{ENV}$ amplitudes ($W = 214.00$, $z = -2.97$, $p = .003$, $r = .53$, $SE = 0.18$) The introduction of CAS had clear amplitude increment.

This significant shift is easy to spot when looking at the raincloud plot (see Figure 4.16). The boxplots show a distinct movement in the median amplitude and a change in the interquartile range once the CAS was introduced. By tracing the lines that connect the individual paired data points, you can see that a majority of the participants experienced a distinct, unified change in their F0 amplitudes under the CAS condition. The probability density curves (the half-violins on the right side of the plot) visually reinforce this, displaying a noticeably altered and shifted distribution of responses during CAS.

The grand average waveform in Figure 4.17 (a) revealed a clear amplitude increment in the complex tone with missing F0 with CAS condition, with CAS amplitude appearing notably elevated at several points across the response window, while the without CAS condition reflected a relative decrement in amplitude throughout. The grand average spectrum in (b) similarly showed higher spectral energy with CAS condition particularly at the lower harmonic peaks, without CAS condition demonstrating comparatively reduced energy across those same frequency regions.

**Objective 4. To compare the spectral amplitude of $FFR_{ENV}$ elicited by the complex tone with and without F0**

The fourth objective of this study was to determine if the neural encoding of the stimulus $FFR_{ENV}$ is significantly altered when the first two harmonics—including the physical F0—are removed from a complex tone. The Figure 4.18 shows median, quartile deviation and individual data points of $FFR_{ENV}$ amplitudes for complex tone and complex

tone with missing F0. From the Figure it can be seen that no change in $FFR_{ENV}$ amplitudes. Figures 4.19 (a) and (b) shows the grand average waveform and spectrum of complex tone and complex tone with missing F0.

**Figure 4.18**

*Median, quartile deviation and individual data points of amplitude of* $FFR_{ENV}$ for complex tone *and* complex tone *with missing F0.*

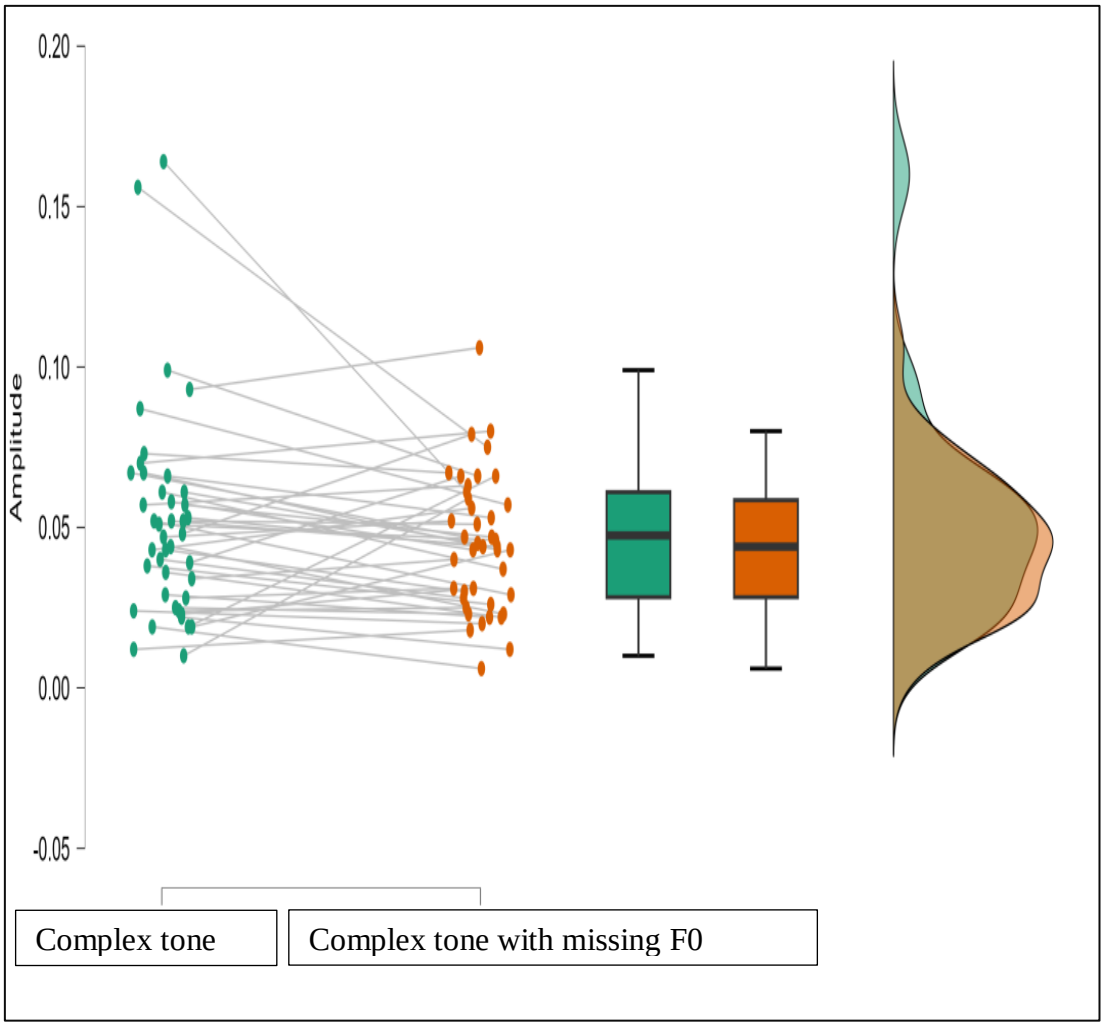
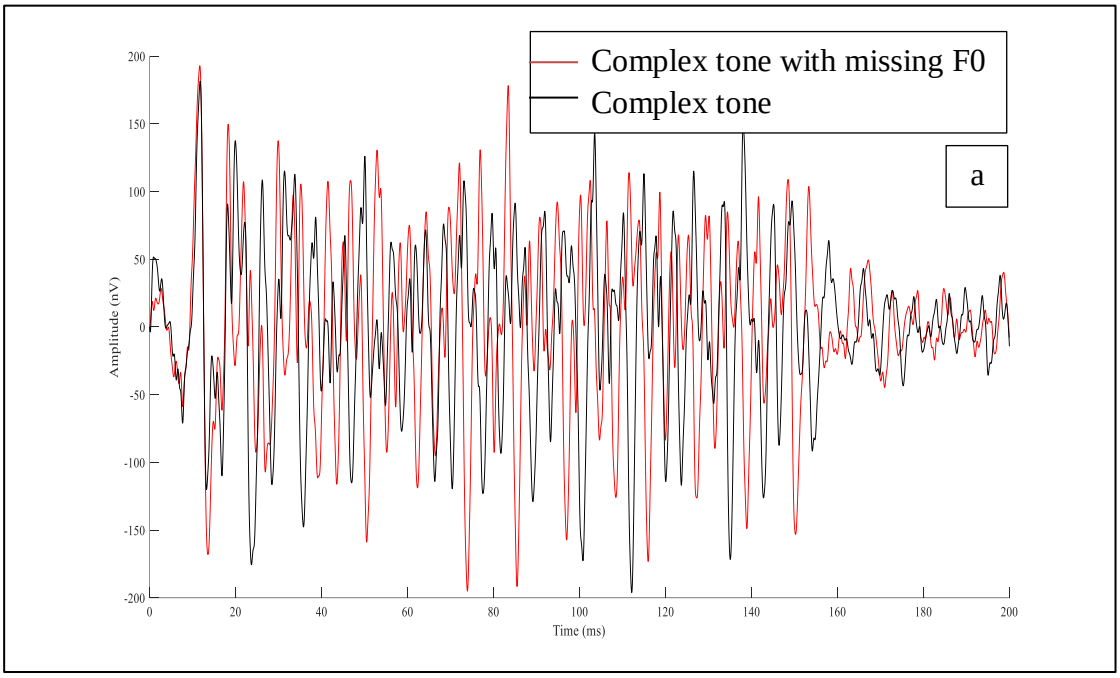
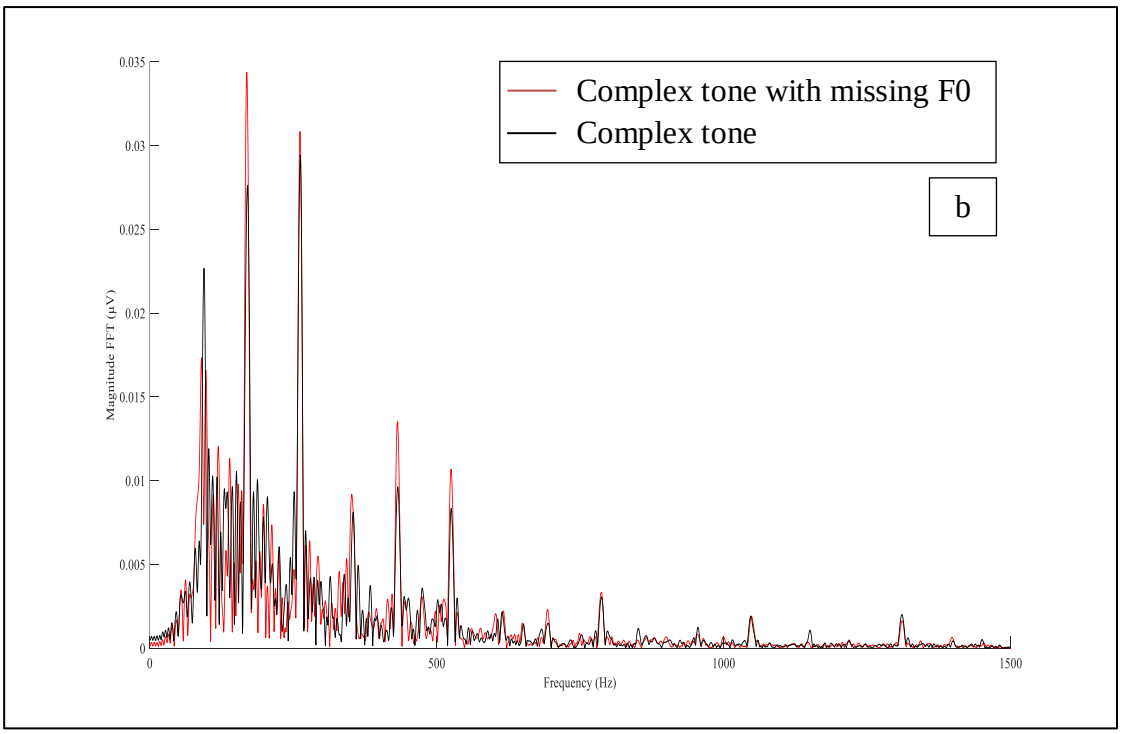


**Figure 4.19**

*Waveform (a) and spectrum (b) of* $FFR_{ENV}$ *amplitude in response to* complex tone *(black) and* complex tone *with missing F0 (red).*



A Wilcoxon signed-rank test was employed to compare the spectral amplitudes of the complex tone and the complex tone with missing F0. The analysis revealed that there was no statistically significant difference in the $FFR_{ENV}$ spectral amplitudes between the two conditions ($W = 602.50$, $z = 1.89$, $p = .060$). Although the p-value approached the threshold of significance, it did not meet the alpha = 0.05 criterion.

As observed in the raincloud plot, the distribution of neural responses and the median amplitudes (represented by the horizontal lines within the boxplots) remained relatively stable even when the physical F0 was missing. The grand average waveform in 4.19 (a) showed marginal amplitude increment in the complex tone with missing F0 condition, though both traces largely followed a comparable pattern throughout the response window. The grand average spectrum in (b) reflected a similar trend, with the complex tone with missing F0 condition showing slightly higher spectral energy at certain harmonic peaks compared to a relative decrement observed in the complex tone F0 condition.

# CHAPTER 5

# DISCUSSION

The present study enrolled 41 adults between the ages of 18 and 30 years, all of whom presented with clinically normal peripheral hearing. This age range was selected to minimize the influence of age-related auditory changes on subcortical neural responses, thereby ensuring that the observed effects could be more attributed to the experiment. Four acoustically distinct stimuli were employed: a 170 ms synthetic /ba/ syllable, a 300 Hz high-pass filtered version of the same /ba/ syllable, a 10-tone harmonic complex with a fundamental frequency of 260 Hz, and the same complex tone with its first two harmonics excluded. The study assessed the spectral amplitudes of both the envelope-following response ($FFR_{ENV}$) and the temporal fine-structure-following response ($FFR_{TFS}$) in the presence and absence of contralateral acoustic stimulation (CAS), in order to understand how efferent-mediated gain control modulates subcortical encoding of speech and complex tonal signals. The results obtained are discussed under two primary aim below.

## Effect of CAS on $FFR_{ENV}$ and the $FFR_{TFS}$

The addition of CAS resulted in enhanced response amplitudes across multiple experimental conditions. Traditional neurophysiological models typically characterize the medial olivocochlear (MOC) efferent reflex as a predominantly inhibitory pathway that suppresses cochlear amplifier gain. Contrary to this traditional view, the application of CAS significantly increased $FFR_{ENV}$ amplitudes for the 300 Hz high-pass filtered speech token and for the complex tone stimuli, both with and without the fundamental frequency. CAS also enhanced $FFR_{TFS}$ amplitudes in the first formant (F1) frequency region of the original /ba/ stimulus. These findings indicate that CAS can facilitate, rather than suppress, neural encoding under certain stimulus conditions, leading to enhanced $FFR_{ENV}$ and $FFR_{TFS}$ amplitudes. These findings, suggest that the efferent auditory system is capable of reshaping

subcortical neural encoding of periodic acoustic signals though the nature and direction of this reshaping is closely tied to the spectrotemporal structure of the eliciting stimulus.

It is well established that the frequency-following response serves as a sensitive, high fidelity neurophysiological window into how the auditory brainstem encodes the temporal and spectral features of complex acoustic signals (Skoe & Kraus, 2010). Critically, the spectral amplitude of the FFR has been widely adopted as a direct indicator of neural phase-locking magnitude, such that higher amplitudes are understood to reflect stronger and more precise subcortical encoding of the periodic features of the stimulus (Mondéjar-Segovia et al., 2025; Russo et al., 2004). This principle has clinical and theoretical significance. Degraded FFR spectral amplitudes have been consistently linked to poorer speech-in-noise perception across diverse populations (Anderson & Kraus, 2010; Song et al., 2011), while enhanced amplitudes have been associated with enriched auditory experience, improved phonological processing, and better speech intelligibility outcomes (Krizman & Kraus, 2019).

The rationale for examining CAS effects on the FFR is directly linked to the functional architecture of the auditory efferent system. The MOC efferent pathway, activated reflexively by CAS , projects from the superior olivary complex to the outer hair cells of the cochlea and serves as a top-down gain control mechanism that modifies cochlear output in response to the auditory environment (Guinan, 2006). Physiologically, MOCR activation causes hyperpolarization of outer hair cells, reduces cochlear amplification, and increases auditory nerve fiber firing rates in the presence of continuous background signals, a process commonly referred to as antimasking (Mertes et al., 2019).

The result of CAS effects on FFR amplitudes draws on a evidence linking efferent system activation to improvements in speech perception under adverse listening conditions. One of the earliest and most influential demonstrations of this principle was provided by

Giraud et al. (1997), who examined phoneme recognition in noise in 20 normal-hearing adults alongside five patients who had undergone vestibular neurotomy a surgical procedure that interrupts olivocochlear efferent fibers. When contralateral broadband noise was introduced, phoneme recognition in noise improved by approximately 5–10% in normal-hearing listeners; this improvement was virtually absent on the operated side of vestibular-neurotomized patients, whose efferent pathways had been severed. The magnitude of CAS-induced improvement in speech perception was significantly and positively correlated with the individual strength of olivocochlear feedback, as indexed by contralateral suppression of otoacoustic emissions (Spearman $r = 0.56$, $p < .01$). Giraud and colleagues interpreted these convergent findings as strong evidence that the MOC efferent pathway plays an antimasking role in speech perception under noise a role mediated through efferent-driven changes in auditory nerve fiber adaptation, intensity coding, and temporal resolution of the basilar membrane, all of which collectively improve the cochlea's capacity to follow the rapid amplitude fluctuations characteristic of speech.

Kumar & Vanaja (2004) evaluated the effect of CAS on speech identification scores in ten normal-hearing children using a within-subjects design. Their results revealed that contralateral stimulation significantly enhanced speech identification performance when the ipsilateral signal-to-noise ratio was +10 dB and +15 dB ($p < .05$ and $p < .01$, respectively), and this behavioural improvement showed a significant positive correlation with the physiological measure of olivocochlear bundle functioning as assessed through contralateral suppression of TEOAE ($p < .001$). Importantly, the improvement was condition specific no significant enhancement occurred at higher SNRs or in quiet a finding that aligns closely with the antimasking hypothesis, which predicts that efferent-mediated gain control is most beneficial precisely when ipsilateral noise is sufficient to saturate auditory nerve fiber responses and reduce their dynamic range. The convergence between a physiological measure

of efferent reflex strength and a psychoacoustic measure of speech recognition in noise, observed in a paediatric sample, further reinforces the view that the medial olivocochlear bundle (MOCB) constitutes a functional mechanism for maintaining speech intelligibility across a range of adverse listening environments.

Mishra and Lutman (2014), in a carefully controlled study of 18 normal-hearing adults, demonstrated that artificially activating the MOC efferents through CAS led to a statistically significant improvement in speech recognition threshold in noise, with a mean CAS-induced signal-to-noise ratio enhancement of 2.45 dB; crucially, this improvement was directly and positively correlated with the magnitude of MOC inhibition indexed through click-evoked otoacoustic emissions ($r$ = .606, $p$ = .008). Their findings underscored not only that the efferent system is capable of improving speech processing under challenging listening conditions, but also that individual differences in efferent reflex strength predict the degree of benefit obtained when CAS is introduced. Similarly, Mertes et al. (2019) demonstrated in a group of 30 normal-hearing young adults that the introduction of CAS significantly improved speech recognition scores at the most adverse signal-to-noise ratio tested (−12 dB), and that the threshold of the psychometric function was significantly correlated with contralateral inhibition magnitude ($rs$ = −0.44, $p$ = .03) providing converging behavioural evidence that the efferent system contributes meaningfully to speech perception under degraded conditions.

Complementing these behavioural perspectives, Jeng et al. (2021) approached the question at the neurophysiological level by examining the effects of contralateral white noise on FFR-derived indices of frequency-coding accuracy in normal-hearing adults. Using a speech stimulus with a rising F0 contour, they found that continuous contralateral noise significantly degraded both tracking accuracy ($t$ = 2.96, $p$ = .009, $d$ = 1.26) and slope error of

the F0 following response suggesting that acoustic signals arriving at the non-test ear can meaningfully disrupt the fidelity of subcortical frequency encoding. The authors proposed that this effect is mediated, at least in part, by both afferent bilateral cross-pathways at the level of the superior olivary complex and the bilateral innervation pattern of the efferent auditory system, noting that the efferent control of frequency coding in the human brain is fundamentally bilateral in nature (Jeng et al., 2021). Together, these lines of evidence justify the present study's approach of using CAS as a means of activating the efferent pathway and examining its downstream consequences for FFR spectral amplitude a more direct neurophysiological index of subcortical encoding strength than the behavioural and otoacoustic measures employed in prior work.

Neurophysiological evaluations in animal models demonstrate that the introduction of this efferent feedback does not purely suppress peripheral auditory activity; rather, it actively improves the detection of transient acoustic signals when they are embedded within steady background noise (Kawase & Liberman, 1993) . This counterintuitive gain modulation acts as an anti-masking mechanism. By selectively adapting the neural response to continuous, uninformative background energy, the efferent system effectively increases the salience and physiological representation of the target transient components (Kawase & Liberman, 1993).

However, the literature does not uniformly support a straightforward beneficial role of the MOCR in speech-in-noise processing. In a methodologically rigorous re-examination of the antimasking hypothesis, de Boer et al. (2012) found that stronger OAE suppression typically interpreted as greater MOC reflex magnitude was paradoxically associated with *poorer* rather than better performance on a consonant-vowel discrimination task in noise involving the /da/–/ga/ contrast ($r = 0.68$, $p < .001$). Furthermore, participants with stronger

OAE suppression exhibited larger noise-induced latency shifts in the speech-evoked auditory brainstem response ($r$ = 0.74, $p$ < .001), indicating that greater MOC activation was associated with more not less brainstem vulnerability to noise masking. De Boer et al. (2012) proposed that this apparently counterintuitive pattern may arise because the functional direction of MOC induced cochlear gain reduction whether beneficial or detrimental depends critically on the acoustic properties of the signal and the spectral region in which masking occurs. Specifically, MOC mediated gain reduction may ameliorate masking produced by on-frequency excitation or suppression, yet aggravate masking produced by an upward spread of excitation, depending on the frequency region involved. Their findings collectively suggest that the MOC system does not act as a uniformly beneficial antimasking device but may instead exert its beneficial effects on speech-in-noise processing through dynamic, attention-driven, and experience-dependent modulation of cochlear gain rather than through reflexive, nonselective gain reduction.

The nuanced and sometimes contradictory picture offered by these studies informed the rationale of the present investigation. Rather than examining behavioural or otoacoustic measures of efferent function, the present study evaluates efferent modulation of subcortical neural encoding more directly, by measuring CAS-induced changes in $FFR_{ENV}$ and $FFR_{TFS}$ spectral amplitudes. Given that stronger spectral amplitudes reflect more precise subcortical encoding (Ananthakrishnan et al., 2016), any CAS-induced increase in FFR amplitude in the present study would provide neurophysiological evidence that efferent activation enhanced brainstem encoding fidelity, a level of analysis that extends beyond and complements the existing literature on behavioural speech intelligibility and OAE suppression.

**Effect of physical F0**

The effect of the F0 is examined across two main categories: speech stimuli /ba/ syllable and complex tones. The spectral amplitude of $FFR_{ENV}$ was significantly higher for the /ba/ with missing F0 condition compared to when F0 was physically present.

One might expect that physically removing energy at the fundamental frequency would weaken neural representation of F0; however, the opposite pattern was observed here, and the effect size was large. Understanding this result requires careful consideration of how harmonic resolvability shapes brainstem phase-locking. (Ananthakrishnan et al., 2021) demonstrated that energy at F0 in $FFR_{ENV}$ arises through neural phase-locking to beat envelopes generated by the interaction of two or more consecutive harmonics on the basilar membrane, and that the response can arise from low, mid, or high frequency stimulus components provided the stimulus envelope is modulated by at least two interacting harmonics. When the physical F0 component is present in a speech signal, it acts essentially as a single low-frequency sinusoid in the lowest region of the spectrum; because single isolated harmonics produce a flat envelope and therefore generate no F0 related envelope modulation on their own, the presence of energy only at F0 provides minimal benefit to $FFR_{ENV}$ encoding (Ananthakrishnan et al., 2021). Removing the physical F0 from the stimulus shifts the spectral energy distribution so that the remaining harmonic components, particularly those in the region of F1 and F2, interact more freely and generate stronger periodic envelope modulation, which in turn drives more robust brainstem phase-locking.

This interpretation is further supported by the role of harmonic resolvability. Ananthakrishnan et al. (2021) found that unresolved harmonics may favorably influence F0 strength in the envelope FFR, and that band-pass filtered stimuli containing only unresolved components produced stronger brainstem responses than stimuli dominated by resolved harmonics of equivalent bandwidth. In speech, the removal of F0 alters the proportional

contribution of unresolved higher order harmonics to the total stimulus energy, potentially shifting the stimulus toward a configuration in which $FFR_{TFS}$ modulation driven by unresolved harmonic interactions is enhanced. This is consistent with the broader theoretical framework proposed by Houtsma and Smurzynski (1990), who showed that pitch perception based on high order unresolved harmonics, while weaker than that from resolved low order harmonics, remains neurally viable and can be conveyed through the $FFR_{TFS}$ periodicity present in $8^{th}$ nerve firing patterns. The auditory system's capacity to derive F0 information from unresolved harmonic interactions, even when the physical F0 is absent, reflects the robustness of temporal pitch coding mechanisms at the brainstem level.

It is also important to consider the broader phenomenon of the missing fundamental in this context. As Houtsma and Smurzynski (1990) established through melodic interval identification experiments, listeners can perceive the pitch of the missing fundamental with accuracy even when harmonic complexes extend from the 20th to the 30th harmonic, well beyond the region of cochlear frequency resolution. Similarly, Clarkson and Clifton (1995) demonstrated that even 7 month old infants can discriminate and categorize tonal complexes based on the pitch of the missing fundamental, suggesting that this neural computation is a fundamental and developmentally early capacity of the auditory system. This developmental robustness underscores the degree to which F0 extraction from harmonic patterns rather than direct encoding of the physical fundamental constitutes the primary mode of pitch computation. That the brainstem shows a stronger $FFR_{ENV}$ response when F0 is absent in speech may therefore reflect the dominance of this pattern based extraction mechanism: without the physical F0 "anchoring" low-frequency energy, the higher harmonics generate a cleaner, more salient periodic envelope that is more efficiently encoded by subcortical neural populations.

***For Complex Tones (Complex tone vs. Complex tone with Missing F0)***

In contrast to the speech stimulus, a Wilcoxon signed-rank test comparing the spectral amplitudes of a standard complex tone (260 Hz F0) and a complex tone with a missing F0 revealed no statistically significant difference ($W$ = 602.50, $z$ = 1.89, $p$ = .060). This null result, while approaching significance, is consistent with the view that brainstem encoding of the F0 for harmonic complex tones is largely invariant to whether F0 energy is physically present in the stimulus. Coffey et al. (2016) reported a highly analogous finding in their experiment. They reported no difference in the FFR amplitude to F0 between conditions in which complex tones contained or lacked physical energy at the fundamental frequency. The consistency between the present results and those of Coffey et al. (2016) across methodologically distinct paradigms lends considerable convergent validity to both sets of findings, and collectively suggests that the brainstem representation of F0 for complex tones is not simply a passive reflection of the acoustic energy at that frequency.

# CHAPTER 6

## SUMMARY AND CONCLUSION

The present study examined the effect of contralateral acoustic stimulation (CAS) on frequency-following response (FFR) spectral amplitudes in 41 normally-hearing adults using four stimuli: a synthetic /ba/ syllable, a 300 Hz high-pass filtered /ba/ syllable (missing F0), a 10-tone harmonic complex tone (260 Hz F0), and the same complex tone with its first two harmonics excluded. Both the envelope-following response ($FFR_{ENV}$) and the temporal fine-structure-following response ($FFR_{TFS}$) were assessed with and without CAS.

Contrary to the conventional suppressive characterization of the medial olivocochlear (MOC) efferent reflex, CAS produced a facilitatory effect on subcortical encoding in multiple conditions. $FFR_{ENV}$ amplitudes were significantly elevated for the high-pass filtered /ba/ syllable ($W$ = 227.50, $z$ = -2.27, $p$ = .024, $r$ = .42) and for both complex tone stimuli, with moderate-to-large effect sizes. In the fine-structure domain, CAS selectively enhanced $FFR_{TFS}$ amplitudes at the first formant frequency (F1) of the original /ba/ syllable ($W$ = 142.00, $z$ = -2.28, $p$ = .022, $r$ = .46), while second formant(F2) and filtered-stimulus responses remained statistically unchanged. These outcomes indicate that the efferent system reshapes brainstem phase-locking in a stimulus specific rather than globally suppressive manner.

Removing the physical F0 from the /ba/ syllable paradoxically strengthened $FFR_{ENV}$ amplitudes compared to the full stimulus ($W$ = 124.50, $z$ = -3.84, $p$ < .001, $r$ = .70), reflecting that higher harmonics produce more robust periodic envelope modulation when freed from the presence of an isolated fundamental component. For the complex tone, $FFR_{ENV}$ amplitudes did not differ significantly between conditions with and without the physical F0 ($p$ = .060), consistent with (Coffey et al., 2016) and confirming that brainstem pitch

representation is sustained by higher-order harmonic extraction regardless of whether the fundamental is acoustically present.

These results establish that CAS modulates subcortical neural encoding in a stimulus dependent, facilitatory manner, and that brainstem F0 representation is grounded in harmonic computation rather than direct acoustic energy at the fundamental. These findings deepen the neurophysiological understanding of olivocochlear efferent function and lay a meaningful foundation for future research in clinical populations who experience difficulty hearing in noise.

## REFERENCES


AIISH. (2023). Ethical Guidelines for Bio-behavioural Involving Human subjects - 2.0.

Ananthakrishnan, S., Grinstead, L., & Yurjevich, D. (2021). Human Frequency Following Responses to Filtered Speech. *Ear and Hearing*, *42*(1), 87–105. https://doi.org/10.1097/AUD.0000000000000902

Ananthakrishnan, S., Krishnan, A., & Bartlett, E. (2016). Human Frequency Following Response: Neural Representation of Envelope and Temporal Fine Structure in Listeners with Normal Hearing and Sensorineural Hearing Loss. *Ear and Hearing*, *37*(2), e91–e103. https://doi.org/10.1097/AUD.0000000000000247

Anderson, S., & Kraus, N. (2010). Objective neural indices of speech-in-noise perception. *Trends in Amplification*, *14*(2), 73–83. https://doi.org/10.1177/1084713810380227

American National Standards. . (1999). Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms. In American National Standards Institute, S3.1-1999. (New York:American National Standards Institute, Vol. 2, Issue 1). https://doi.org/10.1044/1059-0889.0201.33

Carhart, R., & Jerger, J. F. (1959). Preferred Method For Clinical Determination Of Pure-Tone Thresholds. Journal of Speech and Hearing Disorders, 24(4), 330–345. https://doi.org/10.1044/JSHD.2404.330

Cariani, P. A., & Delgutte, B. (1996). Neural correlates of the pitch of complex tones. II. Pitch shift, pitch ambiguity, phase invariance, pitch circularity, rate pitch, and the dominance region for pitch. *Journal of Neurophysiology*, *76*(3), 1717–1734. https://doi.org/10.1152/jn.1996.76.3.1717

Clarkson, M. G., & Clifton, R. K. (1995). Infants' pitch perception: Inharmonic tonal complexes. *The Journal of the Acoustical Society of America*, *98*(3), 1372–1379. https://doi.org/10.1121/1.413473

Coffey, E. B. J., Colagrosso, E. M. G., Lehmann, A., Schönwiesner, M., & Zatorre, R. J. (2016). Individual differences in the frequency-following response: Relation to pitch perception. *PLoS ONE*, *11*(3). https://doi.org/10.1371/journal.pone.0152374

Collet, L., Veuillet, E., Moulin, A., Morlet, T., Giraud, A. L., Michey, C., & Chéry-Croze, S. (1994). Contralateral auditory stimulation and otoacoustic emissions: A review of basic data in humans. *British Journal of Audiology*, *28*(5--Apr), 213–218. https://doi.org/10.3109/03005369409086570

de Boer, J., Thornton, A. R. D., & Krumbholz, K. (2012). What is the role of the medial olivocochlear system in speech-in-noise processing? *Journal of Neurophysiology*, *107*(5), 1301–1312. https://doi.org/10.1152/jn.00222.2011

Delgutte, B. (1990). Physiological mechanisms of psychophysical masking: observations from auditory-nerve fibers. *The Journal of the Acoustical Society of America*, *87*(2), 791–809. https://doi.org/10.1121/1.398891

Durante, A. S., & Oliveira, S. de J. (2020). Frequency-following response (FFR) with speech stimulus in normal-hearing young adults. *CODAS*, *32*(3), 1–6. https://doi.org/10.1590/2317-1782/20202018254

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Gafoor, S. A., & Uppunda, A. K. (2024). Role of the medial olivocochlear efferent auditory system in speech perception in noise: a systematic review and meta-analyses. In *International Journal of Audiology* (Vol. 63, Number 8, pp. 561–569). Taylor and Francis Ltd. https://doi.org/10.1080/14992027.2023.2260951

Galbraith, G. C., Arbagey, P. W., Branski, R., Comerci, N., & Rector, P. M. (1995). Intelligible speech encoded in the human brain stem frequency-following response. *Neuroreport*, *6*(17), 2363–2367. https://doi.org/10.1097/00001756-199511270-00021

Giraud, A. L., Collet, L., Chéry-Croze, S., Magnan, J., & Chays, A. (1995). Evidence of a medial olivocochlear involvement in contralateral suppression of otoacoustic emissions in humans. *Brain Research*, *705*(1–2), 15–23. https://doi.org/10.1016/0006-8993(95)01091-2

Giraud, A. L., Garnier, S., Micheyl, C., Lina, G., Chays, A., & Chéry-Croze, S. (1997). Auditory efferents involved in speech-in-noise intelligibility. *Neuroreport*, *8*(7), 1779–1783. https://doi.org/10.1097/00001756-199705060-00042

Guinan, J. J. (2006). Olivocochlear efferents: anatomy, physiology, function, and the measurement of efferent effects in humans. *Ear and Hearing*, *27*(6), 589–607. https://doi.org/10.1097/01.aud.0000240507.83072.e7

Houtsma, A. J. M., & Smurzynski, J. (1990). Pitch identification and discrimination for complex tones with many harmonics. *The Journal of the Acoustical Society of America*, *87*(1), 304–310. https://doi.org/10.1121/1.399297

Jarvelainen, H., Verma, T., & Valimki, V. (2002). Perception and Adjustment of Pitch in Inharmonic String Instrument Tones. *Journal of New Music Research*, *31*(4), 311–319. https://doi.org/10.1076/jnmr.31.4.311.14167

JASP Team. (2023). *JASP* (Version 0.17.3) [Computer software]. https://jasp-stats.org

Jeng, F. C., Stehura, K. A., Hart, B. N., & Giordano, A. T. (2021). Contralateral noise degrades frequency-coding accuracy in normal-hearing adults – preliminary results. *Proceedings of Meetings on Acoustics*, *45*(1). https://doi.org/10.1121/2.0001516

Johnson, T. A., Cooper, S., Stamper, G. C., & Chertoff, M. (2017). Noise Exposure Questionnaire: A Tool for Quantifying Annual Noise Exposure. *Journal of the American Academy of Audiology*, *28*(1), 14–35. https://doi.org/10.3766/jaaa.15070

Kawase, T., & Liberman, M. C. (1993). Antimasking effects of the olivocochlear reflex. I. Enhancement of compound action potentials to masked tones. *Journal of Neurophysiology*, *70*(6), 2519–2532. https://doi.org/10.1152/jn.1993.70.6.2519

Kraus, Nina., Anderson, Samira., White-Schwoch, Travis., Fay, R. R. ., & Popper, A. N. . (2017). *The frequency-following response : a window into human communication*. Springer.

Krizman, J., & Kraus, N. (2019). Analyzing the FFR: A tutorial for decoding the richness of auditory function. *Hearing Research*, *382*. https://doi.org/10.1016/j.heares.2019.107779

Kumar, U. A., & Vanaja, C. S. (2004). Functioning of olivocochlear bundle and speech perception in noise. *Ear and Hearing*, *25*(2), 142–146. https://doi.org/10.1097/01.aud.0000120363.56591.e6

Lilaonitkul, W., & Guinan, J. J. (2009). Human medial olivocochlear reflex: effects as functions of contralateral, ipsilateral, and bilateral elicitor bandwidths. *Journal of the Association for Research in Otolaryngology : JARO*, *10*(3), 459–470. https://doi.org/10.1007/s10162-009-0163-1

Matsuwaki, Y., Nakajima, T., Ookushi, T., Iimura, J., Kunou, K., Nakagawa, M., Shintani, M., Moriyama, H., & Ishikawa, T. (2004). Evaluation of missing fundamental phenomenon in the human auditory cortex. *Auris, Nasus, Larynx*, *31*(3), 208–211. https://doi.org/10.1016/j.anl.2004.03.016

Mertes, I. B., Johnson, K. M., & Dinger, Z. A. (2019). Olivocochlear efferent contributions to speech-in-noise recognition across signal-to-noise ratios. *The Journal of the Acoustical Society of America*, *145*(3), 1529–1540. https://doi.org/10.1121/1.5094766

Mertes, I. B., & Leek, M. R. (2016). Concurrent measures of contralateral suppression of transient-evoked otoacoustic emissions and of auditory steady-state responses. *The Journal of the Acoustical Society of America*, *140*(3), 2027–2038. https://doi.org/10.1121/1.4962666

Mishra, S. K., & Lutman, M. E. (2014). Top-down influences of the medial olivocochlear efferent system in speech perception in noise. *PLoS ONE*, *9*(1). https://doi.org/10.1371/journal.pone.0085756

Mondéjar-Segovia, A., Gorina-Careta, N., Arenillas-Alcón, S., Koravand, A., Costa-Faidella, J., Ribas-Prats, T., Gómez-Roig, M. D., & Escera, C. (2025). Neural encoding of speech-in-noise in neonates: A frequency-following response study. *The Journal of*

*the Acoustical Society of America*, *158*(3), 2577–2589. https://doi.org/10.1121/10.0039384

Oxenham, A. J. (2008). Pitch Perception and Auditory Stream Segregation: Implications for Hearing Loss and Cochlear Implants. *Trends in Amplification*, *12*(4), 316–331. https://doi.org/10.1177/1084713808325881

Parbery-Clark, A., Skoe, E., & Kraus, N. (2009). Musical experience limits the degradative effects of background noise on the neural processing of sound. *Journal of Neuroscience*, *29*(45), 14100–14107. https://doi.org/10.1523/JNEUROSCI.3256-09.2009

Ribarić, K., Prevec, T. S., & Kozina, V. (1984). Frequency-following response evoked by acoustic stimuli in normal and profoundly deaf subjects. *International Journal of Audiology*, *23*(4), 388–400. https://doi.org/10.3109/00206098409081532

Russo, N., Nicol, T., Musacchia, G., & Kraus, N. (2004). Brainstem responses to speech syllables. *Clinical Neurophysiology*, *115*(9), 2021–2030. https://doi.org/10.1016/j.clinph.2004.04.003

Schiavetti, N., & Metz, D. E. (2006). *Evaluating research in communicative disorders* (5th ed.). Allyn & Bacon.

Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, *52*(3/4), 591–611. https://doi.org/10.1093/biomet/52.3-4.591

Shofner, W. P. (2011). Perception of the missing fundamental by chinchillas in the presence of low-pass masking noise. *JARO - Journal of the Association for Research in Otolaryngology*, *12*(1), 101–112. https://doi.org/10.1007/s10162-010-0237

Skoe, E., & Kraus, N. (2010). Auditory brain stem response to complex sounds: a tutorial. *Ear and Hearing*, *31*(3), 302–324. https://doi.org/10.1097/AUD.0b013e3181cdb272

Smith, S. B., & Cone, B. (2021). Efferent unmasking of speech-in-noise encoding? *International Journal of Audiology*, *60*(9), 677–686. https://doi.org/10.1080/14992027.2020.1862425

Song, J. H., Skoe, E., Banai, K., & Kraus, N. (2011). Perception of Speech in Noise: Neural Correlates. *Journal of Cognitive Neuroscience*, *23*(9), 2268–2279. https://doi.org/10.1162/jocn.2010.21556

Usubuchi, H., Kawase, T., Kanno, A., Yahata, I., Miyazaki, H., Nakasato, N., Kawashima, R., & Katori, Y. (2014). Effects of contralateral noise on the 20-Hz auditory steady state response--magnetoencephalography study. *PloS One*, *9*(6), e99457. https://doi.org/10.1371/journal.pone.0099457

Venkatesan, S., & Basavaraj, V. (2009). Ethical guidelines for bio-behavioral research involving human subjects. All India Institute of Speech and Hearing, Mysore.

Warren, E. H., & Liberman, M. C. (1989). Effects of contralateral sound on auditory-nerve responses. I. Contributions of cochlear efferents. *Hearing Research*, *37*(2), 89–104. https://doi.org/10.1016/0378-5955(89)90032-4

Worden, F. G., & Marsh, J. T. (1968). Frequency-following (microphonic-like) neural responses evoked by sound. *Electroencephalography and Clinical Neurophysiology*, *25*(1), 42–52. https://doi.org/10.1016/0013-4694(68)90085-0

Yathiraj, A., & Vijayalakshmi, C. S. (2005). *Phonemically Balanced Word List in Kannada*. Department of Audiology, All India Institute of Speech and Hearing, Mysore.

Yellamsetty, A., & Bidelman, G. M. (2019). Brainstem correlates of concurrent speech identification in adverse listening conditions. *Brain Research*, *1714*, 182–192. https://doi.org/10.1016/j.brainres.2019.02.025

# ANNEXURE I

**All India Institute of Speech and Hearing**
(An autonomous Institute under the
Ministry of Health and Family Welfare, Govt. of India)
Center of Excellence - Assessed & Accredited by NAAC with 'A' Grade
ISO 9001:2015 Implemented Institute
Manasagangothri, Mysuru-570006

ಅಖಿಲ ಭಾರತ ವಾಕ್ ಮತ್ತು ಶ್ರವಣ ಸಂಸ್ಥೆ
ಮಾನಸಗಂಗೋತ್ರಿ, ಮೈಸೂರು–570006
अखिल भारतीय वाक् श्रवण संस्थान
मानसगंगोत्री, मैसूरु - 570 006

**INSTITUTE REVIEW BOARD (IRB) APPROVAL FOR BIO-BEHAVIOURAL RESEARCH PROPOSAL INVOLVING HUMAN SUBJECTS AT AIISH**

**AIISH Institute Review Board (IRB)**

**Ref: SH/IRB/M.4/AUD.06/2025-26** **Date: 06.01.2026**

| | |
|---|---|
| **Title of the Dissertation** | : Effect of Contralateral Acoustic Stimulation on Frequency Following Responses to Speech And Complex Tone |
| Name of the Investigator | : Vikas Dhar Dwivedi |
| Guide | : Dr. Ajith Kumar U. |
| Co-Guide (if any) | : - |
| Proposed Duration of the Project | : 08 months |
| Source of funding | : Non-funded Master's dissertation |
| Estimated budget | : Nil |
| Reference Number of the Project | : Nil |
| Date on which the IRB meeting was held | : 02.01.2026 |
| **A clear statement of the decision reached IRB meeting (In the vent of the proposal is not approved, a statement of reasons for the same must be indicated)** | : **APPROVED** |
| **Advice & suggestions (if any)** | : NIL |

Signature & Name of the Member Secretary-IRB
Dr. Animesh Barman
Professor of Audiology
All India Institute of Speech and Hearing, Mysore-570006

Member Secretary
Institutional Review Board
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