Exploring Cortical Contributions to Auditory Frequency Following Responses Elicited Using Repetitive and Variable Stimulus Paradigms

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Registration No: P01II24S023018

A Dissertation Submitted in Part - Fulfilment of the

Degree of Master of Science **(Audiology)**

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JUNE, 2026

CERTIFICATE

This is to certify that this dissertation entitled **"Exploring Cortical Contributions to Auditory Frequency Following Responses Elicited Using Repetitive and Variable Stimulus Paradigms"** is a bonafide work submitted as part of fulfilment of the degree of Master of Science **(Audiology)** of the student with Registration Number **P01II24S023018**. 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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This is to certify that this dissertation entitled **"Exploring Cortical Contributions to Auditory Frequency Following Responses Elicited Using Repetitive and Variable Stimulus Paradigms"** has been prepared under my supervision and guidance. It is also being certified that this dissertation has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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DECLARATION

This is to certify that this dissertation entitled **"Exploring Cortical Contributions to Auditory Frequency Following Responses Elicited Using Repetitive and Variable Stimulus Paradigms"** is the result of my own study under the guidance of Dr. Sandeep M., 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

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DEDICATED TO

SHALU, JANSI

AND THE ALMIGHTY

Acknowledgements

Bismillah

Firstly, I would like to express my heartfelt gratitude to my guide, ***Sandeep Sir****. The best decision I ever made was asking him to guide me. Since this was my first time doing research, I was completely new to it and made many mistakes. But he patiently taught me everything from scratch. That patience and dedication is what makes him the* ***BEST TEACHER****. I have learned so much from you, Sir. Thank you for being the sweetest, coolest, and most supportive guide ever!!. Your calmness, encouragement and dedication to teaching never wavered. Looking back, I realise how much I have learnt from you, not just academically but also in approaching challenges with confidence.*

A big thanks to ***Sanjay sir****. Thanking you is a very small thing I could do. I can't thank you enough for all your efforts for helping me complete my dissertation. Your knowledge and foresight inspired me throughout.*

I thank ***Dr. M. Pushpavathi,*** *Director, All India Institute of Speech and Hearing, Mysuru for permitting me to carrying out my dissertation.*

I would also like to thank all the ***lecturers and staff of Audiology****, All India Institute of Speech and Hearing, for helping and guiding me throughout my Master's course.*

A special Thanks to ***Kamalakannan Sir,*** *for all his help in collecting data. Many days you would stay late until 8:00-8:30 PM to assist me in completing my recordings. I am very thankful to you for being patient, guiding and assisting me in this process. I never would have been able to have collected all my data without your help. Thank you for all your support and encouragement on this journey.*

*Thanks and gratitude to **Vibha,** for all her support, encouragement and help for this journey. Despite all the things you had to do, you were always willing to lead me when I needed it. Thank you for being a support, motivator and being there when I needed help! Thank you for your assistance and friendship!*

*Many thanks to **Suraj sir**, for your guidance, teaching and the time you took to help me throughout this journey. Iam truly grateful for your support and encouragement.*

*Special Thanks to **Indira maam,** for her valuable support and inputs.*

*My dearest **Shalu….,** you may be too young to understand what this dissertation means, but you have been one of my biggest motivations throughout this journey. Your hugs, laughter, and innocent conversations brought joy to even the most difficult days. Every milestone I achieved during these two years was motivated by the dream of building a better future for you. Thank you for being my source of happiness, strength and motivation. This achievement is not mine alone, it belongs to you as well. I hope one day, when you read this, you will know how much you inspired me and how proud I am to be your mumma.*

***Jansi,** thank you for always being there for me through this journey. Sometimes I have been stressed, frustrated and overwhelmed, but you have always been there to patiently listen to all my worries and make me keep going. Your understanding, sacrifices and belief in me gave me the strength to overcome every challenge. I knew I had you with me no matter how hard it got. Thank you for being there for me through every high and low and making this journey easy.*

*To my **entire family**, I may not be able to name each one of you, but your constant support and the joy you shared in every small milestone have meant the world to me.*

Innama and Umma, *Your love and sacrifice are the foundation of all my achievements. Even during your own struggles, you never said no to any of my wishes and needs. I promise to always be there for you and strive to make you proud.*

A heartful thank you to my ***dheedhi, Momo, Elepa, Zaidu, Hezzu,****-your love and presence have always meant so much to me.*

Thank you ***Umma, Vaapachi, Fida****,* ***Maryam, Aiishu*** *for your constant support and encouragement and understanding.*

Thank you ***Bhuvana aunty*** *and* ***Sudhakar uncle*** *for being my second parents, always supporting, caring and encouraging me.*

Thank you ***Hamssika*** *for always being my biggest cheerleader, problem solver, and constant support system.*

Thank you ***Amal*** *for being my foodie partner and making even the busiest days a little happier.*

May Allah bless our friendship to last long and strong

Thank you ***Nitish*** *for being willing to come multiple times as a participant for my dissertation.*

Thank you, ***Ruchitha*** *(my dissertation partner)* ***Sonal*** *(my posting partner),* ***Anagha, Hiba, Aksha, Vaishnavi, Zaithuna, Bharath*** *and all my batchmates****.***

I am thankful to the best juniors I have ever got. Thank you ***Arpitha, Gopika, Inas, Minsha, Nihal, Shanthakumar, Ajnas, Arshad, Diksha*** *for your support.*

I would like to thank for all my classmates, my dear juniors and seniors.

To my beloved uppa, *I knowyou can't see this. Your absence is the only scar I carry, yet your beautiful face remains etched in my heart forever. You mean everything to me. Thank you for showering all your blessings.*

May Allah Almighty unite us in Jannah. Ameen

I am thankful to all my participants of this study, without whom my study was impossible to complete. I thank them for being patient enough and spending their valuable time for the study.

There are numerous other people who may have been missed out, but your contributions directly or indirectly are never trivial.

THANK YOU!!

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ABSTRACT

Frequency Following Response (FFR) is an electrophysiological response that reflects phase-locked neural activity to the temporal and spectral characteristics of speech sounds. Traditionally, FFR has been considered to originate predominantly from subcortical auditory structures. However, emerging evidence suggests that cortical auditory regions and corticofugal pathways may also contribute to its generation. The present study aimed to investigate the effect of cognitive engagement on context-dependent encoding in speech-evoked FFRs, thereby providing insights into the potential influence of cortical mechanisms on the neural generators of FFR.

Twenty adults with normal hearing participated in the study. Speech-evoked FFRs were recorded under four experimental conditions: repetitive stimulus without cognitive task, repetitive stimulus with cognitive task, variable stimulus without cognitive task, and variable stimulus with cognitive task. A 100-ms /da/ stimulus presented at 70 dB nHL was used to evoke the responses. Temporal envelope and temporal fine structure components were extracted and analyzed using customized MATLAB scripts. Spectral amplitudes corresponding to the fundamental frequency (F0), harmonics (H2, H3, and H4), and first formant frequency (F1) were measured. In addition, an index of context-dependent encoding was derived by calculating the difference in spectral amplitudes obtained from the repetitive and variable stimulus paradigms.

Statistical analyses revealed a significant main effect of cognitive task engagement on H2 and H3 amplitudes, with higher amplitudes observed during the cognitive task condition compared to the no-task condition. No significant effects of cognitive task engagement were found for F0, H4, or F1 amplitudes. Furthermore, no significant main effect of stimulus paradigm was

observed for any of the measured FFR components. The derived index of context-dependent encoding also failed to demonstrate a consistent pattern of context-dependent neural encoding across participants.

Overall, the findings indicate that cognitive engagement selectively influences specific spectral features of the speech-evoked FFR, whereas the effect of stimulus context appears to be minimal. The observed enhancement of H2 and H3 amplitudes during cognitive task performance suggests modulation of auditory brainstem processing by higher-order neural mechanisms. However, the absence of corresponding changes in other FFR components and the lack of robust context-dependent encoding warrant cautious interpretation. Taken together, these findings provide indirect evidence for the involvement of cortical and corticofugal mechanisms in shaping scalp-recorded FFRs. Further investigations employing more demanding cognitive tasks, high-density EEG recordings, advanced source-localization techniques, and direct measures of cortical activity are needed to better elucidate the contribution of cortical processes to speech-evoked auditory neural encoding.

Keywords: frequency following responses, cognitive task, stimulus paradigm, brainstem, auditory cortex

CHAPTER 1

INTRODUCTION

Event-related potentials (ERPs) are small voltage fluctuations generated in the brain in response to specific stimuli or events (Blackwood & Muir, 1990). Broadly, ERPs can be divided into two categories. The early components, occurring within the first 100 ms of stimulus onset are termed sensory or exogenous ERPs because they depend largely on the physical properties of the stimulus (Sur & Sinha, 2009). These early responses have significant clinical utility in detecting disorders of sensory end organs and brainstem function, and are routinely used in audiology clinics as well as in the evaluation of brain injury and coma (Halliday, 1982; Chiappa, 1990). In contrast, later ERPs reflect higher-order stimulus evaluation and are referred to as cognitive or endogenous ERPs, as they index perceptual and cognitive operations of the brain (Sur & Sinha, 2009; Başar et al., 1984).

In the auditory domain, neural encoding of complex sounds such as speech can be measured non-invasively from subcortical levels of the central nervous system, particularly through auditory brainstem responses - ABR (Johnson et al., 2008). In individual with normal auditory function, ABRs elicited by speech stimuli preserve the temporal and spectral fidelity of incoming sounds, including the harmonic structure of speech (Kraus & Nicol, 2005). ABRs recorded using syllables with plosives, comprises two distinct components: (i) a transient onset response and (ii) a sustained frequency-following response (FFR) that reflects neural phase-locking to stimulus periodicity (Skoe & Kraus, 2010). The FFRs provide a robust index of synchronous sound-evoked brain activity, offering unique precision for assessing auditory processing (Chandrasekaran & Kraus, 2010; Kraus et al., 2017).

FFRs capture spectrotemporal features of auditory signals with high fidelity and are considered to serve as a neural representation of sound within the auditory system (Bidelman, 2018). Traditionally, the inferior colliculus and cochlear nucleus have been regarded as the primary neural generators of the FFR (Marsh et al., 1974; Smith et al., 1975; Chandrasekaran & Kraus, 2010). Evidence from animal studies, such as cryogenic cooling of the inferior colliculus and resection of colliculocortical pathways, supports this view (Smith et al., 1975; Greenberg et al., 1981). However, more recent findings suggest that cortical regions, particularly the auditory cortex, may also contribute to scalp-recorded FFRs, more so under specific stimulus and task conditions (Coffey et al., 2016, 2017; Gnanateja et al., 2021; Hartmann & Weisz, 2019).

Coffey et al. (2016) using a simultaneous Magnetoencephalography (MEG) and Electroencephalography (EEG) recordings demonstrated significant right-lateralised cortical contributions to the FFR at the fundamental frequency of the stimulus, in addition to the activity arising from traditional subcortical auditory structures, including cochlear nucleus, inferior colliculus, and medial geniculate body. Further evidence using combined EEG and functional magnetic resonance imaging revealed that stronger FFR-F0 encoding was associated with increased blood oxygen level dependent activity in the right auditory cortex, supporting cortical involvement in the encoding of periodicity of sound. (Coffey et al., 2017).

Gnanateja et al. (2021) in his EEG-based study demonstrated robust cortical FFRs localized primarily within the Heschl's gyrus and thalamo-recipient layers of the auditory cortex that contribute to scalp-recorded FFRs through volume conduction. Consistent with these findings, Hartmann and Weisz (2019) using MEG recordings during inter modal attention task, demonstrated through source localisation analysis that among the regions exhibiting measurable FFR activity, only the right auditory cortex showed significant attentional

modulation. These findings suggest that attention related changes in scalp recorded FFRs may partly arise from cortical auditory processing rather than solely from subcortical structures (Hartmann & Weisz, 2019). Furthermore, these findings suggested that cortical auditory regions contribute to the scalp-recorded FFR through top-down corticofugal influences in addition to the traditionally known subcortical generators (Hartmann & Weisz, 2019). This implies that the neural processing represented by the FFR is integrated across multiple levels of auditory pathway (Schüller et al., 2023).

The auditory system is composed of the ascending and descending pathways, which allow higher order cognitive processes to influence auditory processing at different levels (Lehmann & Schönwiesner, 2014). For example, Chandrasekaran et al. (2009) demonstrated context-dependent encoding, wherein differences emerged in FFRs elicited under repetitive versus variable stimulus paradigms. This context-dependent modulation has been interpreted as evidence of online plasticity, shaped by stimulus probability and mediated via corticofugal pathways (Chandrasekaran et al., 2009; Gnanateja et al., 2013).

Supporting this view, Maruthy et al. (2017), using repetitive and variable speech stimulus paradigms, reported enhanced encoding of the F0 in repetitive stimulus paradigm, suggesting the presence of corticofugal or top-down cortical modulation of the subcortical auditory nuclei, particularly the inferior colliculus. These corticofugal pathways allow top-down modulation of early auditory processing by signals from cortical regions, providing a potential mechanism for how cognitive factors such as attention and task demands can affect neural encoding (Chandrasekaran et al., 2009; Maruthy et al., 2017). The findings provide indirect evidence for the cortical contributions to scalp recorded FFR.

Attention is a fundamental cognitive process that enables individuals to focus on relevant information while suppressing irrelevant inputs (Schüller et al., 2023). Cortical event

related potentials are enhanced when attention is selectively directed towards auditory stimuli, reflecting modulation by higher levels of auditory processing (Galbraith & Kane, 1993). Furthermore allocation of attention to a competing task can reduce early auditory cortical activity, indicating that sensory processing is influenced by limited and shared attentional resources (Xie et al., 2018).

In contrast to cortical responses, influence of attention on brainstem responses such as FFR remains unclear and has yielded inconsistent findings across studies (Galbraith & Kane, 1993; Hairston et al., 2013; Xie et al., 2018). Galbraith and Kane (1993) found no significant differences in the FFR between baseline, auditory attention and visual attention conditions, but significant attentional effects were observed in cortical ERPs, suggesting that early auditory encoding may remain relatively stable under certain attention tasks. Subsequently, some studies have demonstrated that FFR amplitudes are enhanced when stimuli are attended, suggesting attentional modulation may extend to subcortical levels (Forte et al., 2017; Galbraith et al., 1998; Lehmann & Schönwiesner, 2014). Using a dichotic listening paradigm, FFR spectral amplitude was reported to be significantly greater for attended speech stream compared to the unattended stream, indicating attentional modulation at the subcortical level (Lehmann & Schönwiesner, 2014). Forte et al. (2017) demonstrated that the brainstem response to the attended speaker was larger and more temporally precise compared to an ignored speaker, providing evidence for top-down attentional enhancement of subcortical auditory encoding.

In contrast, Hairston et al. (2013) found a suppression of the FFR when participants engaged in a concurrent cognitive task, regardless of whether the task was auditory or visual in nature, and suggested that the current focus of attention can exert a global, top-down effect on the quality of early auditory encoding.

Xie et al. (2018) studied the influence of visual perceptual load on early auditory representation using repetitive and variable speech stimulus paradigms, and found that increasing visual attentional load modified the decodability of FFRs depending on the predictability of input stimuli. These conflicting results indicates that attentional effects on FFR are complex and may be subject to task, stimulus and experimental considerations (Hairston et al., 2013; Xie et al., 2018). However, FFR, if modulated by attention provides evidence for the involvement of auditory cortex in shaping subcortical responses (Coffey et al., 2016; Hartmann & Weisz, 2019; Kraus & White-Schwoch, 2015).

Since FFR primarily reflects phase-locked neural activity arising from subcortical sources such as inferior colliculus, any systematic modulation of the FFR by top-down attentional processes necessarily implicates descending cortical influences on these early auditory structures (Coffey et al., 2016; Kraus & White-Schwoch, 2015). When attentional resources are engaged by a cognitive task, the auditory cortex is thought to employ these descending pathway in an inhibitory manner, reducing the neural encoding of task-irrelevant sounds at the brainstem level (Hairston et al., 2013). Beyond attentional effects, the presence of a competing cognitive task can also reduce auditory processing (Hairston et al., 2013; Xie et al., 2018) and if so suggests the existence of limited or shared attentional resources. This points to the early auditory encoding not being fully automatic, but being influenced by the cognitive workload of the listener (Xie et al., 2018), in turn influenced by cortical contributions.

1.1 Need for the Study

The FFR, well known as a component of the brainstem responses, reflects neural phase-locking to the fundamental frequency (F0) and its harmonics. While the FFR is primarily generated at subcortical levels, converging evidence from EEG and MEG studies indicates cortical contributions as well (Coffey et al., 2016, 2017; Gnanateja et al., 2021). These studies

have demonstrated cortical involvement in addition to the subcortical sources in the FFR generation, implying that the FFR reflects integrated neural processing across multiple levels of the auditory pathway (Coffey et al., 2016; Schüller et al., 2023). This finding is of considerable importance for understanding the neural mechanisms underlying auditory processing as reflected in FFRs, and for drawing inferences about the effects of pathology and training-related plasticity on the FFR.

Further evidence of cortical involvement comes from studies examining context-dependent modulation of the FFR. Chandrasekaran et al. (2009) compared FFRs recorded using repetitive and variable stimulus paradigms and reported that typically developing children exhibited enhanced brainstem representation of pitch-related cues in the repetitive context relative to the variable context. These findings were attributed to corticofugal influences, suggesting that cortical mechanisms can modulate brainstem encoding as reflected in the FFR.

Cognitive factors such as attention and task engagement are known to influence auditory processing, in addition to stimulus-related effects. Limited attentional resources may reduce auditory processing efficiency, particularly in the presence of a competing cognitive task (Xie et al., 2018). Importantly, while stimulus context and attention factors have been demonstrated to affect auditory processing independently (Chandrasekaran et al., 2009; Xie et al., 2018), their combined influence on FFR has not been explored in a systematic manner (Coffey et al., 2016). Addressing the gap is essential for advancing our understanding of the interaction between cortical and subcortical processes in auditory perception.

In the present study the independent variable included repetitive and variable stimulus paradigms, as well as cognitive task engagement, wherein participants either performed a simple mathematical calculation task or remained in no task condition. The dependent variables were the FFR measures specifically the F0 spectral amplitude and harmonic amplitudes

obtained from the envelope FFR, along with the first formant (F1) amplitude measured from the fine structure FFR.

If a significant effect of cognitive task engagement on the FFR is found, this would indicate that early auditory encoding at the brainstem level is not fully automatic, but is susceptible to top-down modulation by higher cortical processes, providing indirect evidence for cortical contributions to the FFR mediated through the descending corticofugal pathways from the auditory cortex to subcortical generators such as inferior colliculus. Moreover, if the context-dependent changes in the FFR depend on cognitive task engagement, this would suggest an interaction between the predictability of the stimuli and attentional load in the subcortical encoding of sound, indicative of a dynamic interaction between bottom-up stimulus-driven and top-down cortical modulation. Alternatively, if no significant effect of cognitive task engagement is observed on the FFR, this would imply that early subcortical auditory encoding is relatively robust and automatic, and that corticofugal modulation may not be strong enough under the current task conditions to alter brainstem responses, with the FFR reflecting predominantly subcortical processing that is largely independent of concurrent cognitive demands.

Therefore, the present study was conceptualized to systematically investigate changes in FFR between repetitive and variable stimulus paradigms under conditions with and without cognitive task engagement. By analysing the relationship between stimulus context and cognitive demand, the study seeks to shed further light on cortical contributions to FFR and to comprehend how top-down modulation influences early auditory encoding.

1.2 Aim of the Study

The study aimed to explore effect of attention on the context dependent encoding of FFR thereby inferring on the influence of cortical areas and corticofugal pathways on the generators of FFR by employing cognitive task engagement.

1.3 Objectives of the Study

The objectives of the study were:

1. To assess the effect of cognitive task engagement on FFRs recorded using the repetitive and variable paradigms.
2. To assess the effect of stimulus paradigm on FFRs.
3. To assess the effect of cognitive task engagement on context dependent encoding of FFRs.

CHAPTER 2

REVIEW OF LITERATURE

In recent years, speech-evoked auditory brainstem responses (ABRs), particularly Frequency Following Responses (FFRs), have gained considerable attention due to the valuable insights they provide into the neural encoding of complex speech sounds. Traditionally, the auditory brainstem was viewed as a passive relay station that merely transmitted acoustic information to higher cortical centers. However, accumulating evidence indicates that lower auditory structures play an active role in speech processing and dynamically interact with cortical mechanisms through top-down modulatory pathways. This chapter critically reviews and synthesizes the existing literature on the significance of speech-evoked FFRs in understanding the neural encoding of speech. Specifically, it examines the representation of key speech features such as the fundamental frequency, harmonics, and formants; explores context-dependent neural encoding using repetitive and variable stimulus paradigms; and discusses the potential influence of cortical and cognitive mechanisms on speech-evoked auditory processing.

2.1 Frequency Following Responses

ABR elicited by speech stimuli have received much attention in the last two decades. The ABR to a speech stimulus basically has three main components, the onset response, the FFR and the offset response (Greenberg, 1980; Skoe & Kraus, 2010). FFRs are measures of phase locked neural activity that is synchronized to periodic and transient aspects of stimulus. Typically, in humans, FFRs have been measured using the far-field approach (Coffey et al., 2019).

FFR is a sustained auditory evoked potential which mimics the oscillations in the stimulus and is believed to be originating primarily from the inferior colliculi and the rostral brainstem structures (Krishnan & Gandour, 2009; Russo et al., 2004).

FFRs can be elicited using periodic and quasi periodic stimuli such as vowels, consonant vowel syllables, pure tones and speech like sounds (Skoe & Kraus, 2010). The syllable /da/ has been frequently used among these, as it contains both transient and sustained acoustic components, and FFRs elicited for it can reflect representation of both the components, in the auditory system (Skoe & Kraus, 2010). The response preserves both the temporal and spectral features of speech, and thus provide valuable insight into neural encoding of complex speech sounds (Johnson et al., 2008; Skoe & Kraus, 2010).

Subsequently, FFRs capacity to convey neural encoding of crucial speech characteristics such as the fundamental frequency (F0), harmonics, formants is one of its main advantages. The spectral components have been derived through subjecting FFRs to FFT and the output will be the amplitude of the spectral components (Aiken & Picton, 2008; Skoe & Kraus, 2010). The F0 which mostly reflects the pitch of the voice, is of great help for speaker identification and separation of conflicting speech signals. Harmonics and formant related cues improve phoneme recognition and voice clarity. Thus FFRs provide an objective measure of the fidelity of speech representation in the auditory system (Chandrasekaran & Kraus, 2010; Krishnan & Gandour, 2009; Skoe & Kraus, 2010). FFR has been shown to preserve both envelope and temporal fine structure (TFS) information of speech signals (Aiken & Picton, 2008; Ananthakrishnan et al., 2016). While the envelope representation is primarily by the F0 and harmonic components, whereas TFS representation is reflected by formant related components of speech (Ananthakrishnan et al., 2016; Johnson et al., 2008). Both envelope and TFS cues are essential for speech perception, particularly in adverse listening environment (Lorenzi et al., 2006).

Envelope cues represent relatively slow variations in the amplitude of the speech signal and contribute to the perception of speech rhythm, syllable structure, duration, and overall speech intelligibility (Rosen, 1992; Shannon et al., 1995). In contrast, TFS cues represent rapid oscillatory variations within the speech waveform and provide important information regarding pitch, formant structure, vowel identity and speaker characteristics (Moore, 2008; Rosen, 1992). While envelope cues can alone support speech recognition in quiet listening conditions (Shannon et al., 1995), TFS cues play a critical role in speech perception in the presence of competing background noise by facilitating sound source segregation and enhancing the ability to utilize temporal dips in the masker (Hopkins & Moore, 2009; Lorenzi et al., 2006; Smith et al., 1975).

Sensorineural hearing loss selectively impairs the ability to use TFS cues while leaving envelope processing largely intact, which accounts for the disproportionate difficulty hearing-impaired individuals experience when listening in fluctuating background noise (Lorenzi, et al., 2006; Moore, 2016). Consequently, efficient utilization of both envelope and TFS cues is necessary for accurate speech perception in everyday listening situations (Moore, 2008).

Variations in these spectral components across different experimental paradigms may shed light on the role of the stimulus context and higher order auditory mechanisms in speech encoding. Chandrasekaran et al. (2009) demonstrated that spectral amplitudes of the second (H2) and fourth (H4) harmonics were significantly enhanced in the repetitive or high predictable stimulus condition compared to the variable or low predictable condition and the magnitude of this enhancement correlated with the speech in noise perception scores, indicating that the brainstem representation of harmonic component is dynamically shaped by the statistical predictability of the acoustic context.

Variations in F0 and formant-related harmonic amplitudes have also been observed across paradigms with different acoustic environments and listener expertise; reverberation has been shown to selectively degrade the neural encoding of formant-related harmonics much more than that of the fundamental frequency, with musicians showing more robust spectral representations than non-musicians across listening conditions, suggesting that higher-order factors such as musical experience differentially modulate the encoding of individual spectral components (Bidelman, et al., 2011).

Musicians exhibit significantly larger FFR amplitudes for harmonics than non-musicians and the magnitude of the enhancement correlates with years of musical training, suggesting experience-dependent plasticity in subcortical spectral encoding at the individual level (Musacchia et al., 2007 ; Parbery-Clark et al., 2009).Collectively these findings suggest that F0, harmonics and formant amplitudes in the FFR are not fixed neural outputs but are instead sensitive to the interplay between stimulus statistics, listening environment, and auditory experience. Thus understanding the neural mechanisms of speech evoked FFRs is important for interpreting context dependent and cognitively mediated changes in auditory processing.

Although the FFR is widely recognised as a reflecting phase-locked neural activity synchronized to periodic acoustic stimuli, substantial evidence has traditionally supported a predominantly brainstem origin for the response (Chandrasekaran & Kraus, 2010; Skoe & Kraus, 2010). In early studies, the inferior colliculus and cochlear nucleus were identified as the primary neural generators of the scalp-recorded FFR (Marsh et al., 1974; Smith et al., 1975; Chandrasekaran & Kraus, 2010).

Marsh et al. (1974) demonstrated that the FFR closely followed the periodicity of acoustic stimuli and exhibited response latencies consistent with neural activity arising from

brainstem auditory pathways. The authors further noted that the phase-locking features of the response were very similar to the temporal coding characteristics of neurons in the auditory brainstem, which suggests that the FFR is generated subcortically (Marsh et al., 1974).

Smith et al. (1975) provided some of the earliest evidence regarding the neural origins of the FFR. Through a comparison of scalp recorded FFRs and intracranial recordings obtained from successive auditory nuclei in cats, the researchers observed a strong temporal correspondence between the onset latency of the scalp recorded response and activity within the IC (Smith et al., 1975). Furthermore, cryogenic cooling of the IC resulted in a marked reduction or elimination of the FFR, leading the authors to conclude that the IC is the primary generator of the scalp recorded response (Smith et al., 1975).

Greenberg et al. (1981) demonstrated that interrupting the colliculocortical pathways did not eliminate the FFR, indicating that cortical activity was not essential for generating the response and providing evidence for the role of subcortical auditory structures as the primary generators. Subsequent lesion studies further strengthened this view by showing the lack of FFRs in individuals with upper brainstem pathology, thus emphasizing the necessity of intact brainstem structures for the generation of the response (Sohmer et al., 1977). More recently, source localization studies utilizing high-density electroencephalographic recordings have provided converging support for a dominant subcortical contribution to the FFR (Bidelman, 2015, 2018; Bidelman & Momtaz, 2021).

Bidelman (2015) showed that the strongest phase-locked activity driving the response originated in the auditory nerve and inferior colliculus, whereas cortical contributions were comparatively weaker and predominantly limited to lower frequencies. Bidelman (2018) similarly found that for most speech-relevant frequencies subcortical sources contributed significantly more to the scalp-recorded FFR than cortical auditory regions. In addition, source-

level analyses revealed that brainstem components of the FFR were significantly related to speech-in-noise perception, whereas cortical components showed little relationship to behavioural performance (Bidelman & Momtaz, 2021). Collectively, all of these findings from latency analyses, intracranial recordings, cooling experiments, lesion studies, and source localization investigations have consistently identified the inferior colliculus as the dominant generator of the scalp-recorded FFR and established the response as an objective measure of subcortical auditory encoding and neural phase-locking of the auditory brainstem (Chandrasekaran & Kraus, 2010; Skoe & Kraus, 2010).

2.2 Cortical Contributions to FFR

Traditionally, the inferior colliculus and cochlear nucleus have been regarded as the primary neural generators of the FFR (Marsh et al., 1974; Smith et al., 1975; Chandrasekaran & Kraus, 2010). Early evidence supporting this view came from animal studies (Smith et al., 1975), which demonstrated through cryogenic cooling of the inferior colliculus that the neural activity originating from this structure was critical for the generation of the FFR. The substantial reduction in the amplitude of FFR observed during the cryogenic cooling established the IC as the major neural generator of response (Smith et al., 1975).

Greenberg et al. (1981) showed that the resection of colliculocortical pathways did not eliminate the FFR, further reinforcing the subcortical, particularly inferior collicular, origin of the response and suggesting that cortical input was not necessary for its generation.

However, recent evidence has challenged this traditional assumption and suggested possible cortical contributions to scalp recorded FFRs (Coffey et al., 2016, 2017). It has been demonstrated that cortical auditory areas, especially the auditory cortex, can contribute to scalp recorded FFRs under certain stimulus and recording conditions (Coffey et al., 2016; Gnanateja et al., 2021). Coffey et al. (2016) used simultaneous electroencephalography and

magnetoencephalography recordings to demonstrate the contribution of cortical phase locked activity to scalp recorded FFRs. Specifically source localisation of MEG data revealed that the right primary auditory cortex and right planum temporale were significantly involved in generating phase locked activity at the fundamental frequency and its harmonics, with the cortical contribution being particularly evident at lower fundamental frequency where phase locking limits of cortical neurons are not exceeded.

Coffey et al. (2016) thus suggested that scalp recorded responses may reflect integrated neural activity arising from both cortical and subcortical auditory structures, and that relative cortical contribution varies with stimulus characteristics such as the fundamental frequency and its harmonics.

Further evidence using combined electroencephalography and functional magnetic resonance imaging (FMRI) demonstrated cortical correlates of auditory frequency-following and onset responses (Coffey et al., 2017). Coffey et al. (2017) observed BOLD signal changes in auditory cortex, including Heschl's gyrus and superior temporal gyrus, time-locked to the periodicity of the acoustic stimulus, in this study, providing hemodynamic evidence that auditory cortical regions are recruited during the generation of frequency-following activity. Crucially, the cortical BOLD responses correlated with the magnitude of the scalp-recorded FFR, demonstrating a functional relationship between the cortical neural generators and the far-field electrophysiological response, and implying that the auditory cortex does not passively process speech but actively contributes to the sustained phase-locked activity observed in the FFR (Coffey et al., 2017).

Attentional state may influence auditory cortical generators contributing to the FFR suggesting a possible involvement of higher order cortical and cognitive mechanisms during FFR recording (Hartmann & Weisz, 2019). Hartmann and Weisz (2019) examined how the

generators of the FFR are modulated by selective attention by employing a cross modal attention paradigm in which participants were cued to attend to either the visual or auditory modality while being simultaneously presented with repeated /da/ stimuli, using whole head magnetoencephalography for data acquisition. Source reconstruction was performed over regions of interest that included both subcortical and cortical auditory structures including cochlear nucleus, inferior colliculus, medial geniculate nucleus and the auditory cortex bilaterally. First, the results confirmed the strong contribution of cortical regions to the FFR, consistent with previous findings by Coffey et al. (2016).

Crucially, when looking at auditory attention versus visual attention, only the right primary auditory cortex showed a significant attentional modulation of FFR activity at the fundamental frequency, while subcortical generators such as the inferior colliculus and cochlear nucleus were not affected by the attentional manipulation (Hartmann & Weisz, 2019). This was especially relevant as previous EEG investigations used a limited number of scalp electrodes and attributed effects of attention directly to subcortical structures without source analysis, resulting in inconsistent findings in the literature. These results suggest that the attentional effects on the FFR are cortical rather than subcortical in origin, and that the higher order cognitive engagement during FFR recording modulates the response through its cortical generators, emphasizing the contribution of top-down corticofugal mechanisms in the formation of the scalp-recorded FFR.

Further evidence for cortical contributions to the scalp recorded FFR was provided by (Gnanateja et al., 2021) who employed a cross species approach combining direct intracortical recordings in humans along with intracranial and extracranial recordings in animal models such as rhesus macaques and guinea pigs owing to their vocal communication abilities and the anatomical and physiological similarities of their auditory pathways to those of humans. They

demonstrated clear cortical FFRs across all species and reported that these responses primarily originated from the thalamorecipient layers of the auditory cortex.

In addition, cortical activity was shown to contribute to the scalp-recorded FFR via volume conduction mechanisms and representational similarity analyses demonstrated similar cortical FFR features in human and animal models (Gnanateja et al., 2021). Based on these findings, the authors proposed that the scalp-recorded FFR reflects integrated neural activity from distinct hierarchical levels of the auditory pathway, such as cortical and subcortical sources and showed that cortical activity contributes to scalp recorded FFR through volume conduction mechanisms (Gnanateja et al., 2021). These findings indicated that scalp recorded FFRs might represent integrated neural activity from diverse hierarchical levels of the auditory pathway (Gnanateja et al., 2021). However, the relative contributions of cortical and subcortical sources to scalp recorded FFRs are still controversial (Behroozmand et al., 2016; Bidelman, 2015, 2018; Guo et al., 2021). Although there is scientific evidence for subcortical as well as cortical sources of FFRs, (Bidelman, 2018) proposed that subcortical generators continue to dominate scalp recorded neuroelectric FFRs, particularly for speech stimuli, whereas the cortical contribution may emerge under certain stimulus conditions and recording methodologies.

2.3 Context Dependent Encoding of Speech

Context dependent encoding of speech refers to the modulation of auditory neural responses based on stimulus predictability and acoustic context (Chandrasekaran et al., 2009). Context dependent brainstem encoding is an indicator of the influence of active feedback mechanisms that functions online. Chandrasekaran et al. (2009) recorded FFRs to syllable /da/ in repetitive/high predictable and variable/ low predictive stimulus conditions. Responses recorded in the repetitive/high predictable condition showed increased spectral amplitudes in

the low harmonics and first formant region compared to the variable/low predictable condition. This context-dependent modulation has been interpreted as evidence of online plasticity, shaped by stimulus probability and mediated via corticofugal pathways (Chandrasekaran et al., 2009; Gnanateja et al., 2013). Importantly, such context-dependent encoding has been shown to play a functional role in enhancing speech perception in noise (Chandrasekaran et al., 2009; Maruthy et al., 2017).

Similarly, Skoe and Kraus (2010) reported enhanced representation of musical notes in the brainstem in a repeatedly presented melody indicating that the encoding in the auditory brainstem is affected by the statistics of the sound currently presented via corticofugal feedback mechanisms. They found prolonged latencies of onset and sustained responses under contextual conditions compared to repetitive conditions, suggesting possible modulation of auditory brainstem encoding through corticofugal pathways.

Spectral structure was found to be an important cue for context dependent encoding of speech, suggesting that spectral variations within contextual stimuli can influence the auditory brainstem representation of speech sounds (Gnanateja et al., 2013). Enhanced neural encoding of the fundamental frequency was demonstrated in repetitive/high-predictable situations among musicians compared to non-musicians, and neural encoding precision was found to correspond with musical training and speech perception in noise abilities (Parbery-Clark et al., 2011). Amplitudes of the FFR differed between the repetitive and contextual conditions, in both quiet and noise, suggesting that the context of the stimulus and the listening environment affect the neural encoding of speech (Shruthi, 2018).

Collectively, these studies suggest that the encoding of the auditory brainstem is dynamically influenced by the stimulus predictability, contextual acoustic information and corticofugal mechanisms (Chandrasekaran et al., 2009; Skoe & Kraus, 2010).

Context dependent modulation of speech evoked FFR has been shown in previous studies with repetitive and contextual stimulus conditions, however limited literature has examined whether such modulation is influenced by a simultaneous cognitive task engagement.

2.4 Corticofugal Modulation of FFR Generation and Cognitive Influence on FFR

The corticofugal refers to the descending auditory pathways through which cortical auditory regions influence subcortical auditory processing (Suga, 2002; Suga et al., 2008). These pathways are thought to regulate auditory encoding based on the importance of stimulus, attentional and listening demands (Chandrasekaran & Kraus, 2010; Suga, 2008). There is a reason to suspect corticofugal tuning mechanism for auditory processing. Feedback related top-down projections may be based on massive efferent connections from cortex to subcortical auditory structures (Kral & Eggermont, 2007). In addition, efferent connections between layers of the auditory cortex exert excitatory and inhibitory control over the inferior colliculus (Keurghlian & Knudsen, 2007).

Animal studies have shown that cortical stimulation can change the response properties of neurons in the inferior colliculus, supporting the role of corticofugal modulation in auditory processing (Gao & Suga, 2000; Zhang & Suga, 1997). These findings imply that auditory processing is not simply governed by ascending sensory input but is constantly modified by cortical feedback mechanisms contingent upon the contextual and behavioural needs (Suga, 2008).

Attention and cognitive engagement have also been shown to affect auditory neural processing, in addition to the stimulus context (Galbraith & Kane, 1993; Hartmann & Weisz, 2019). Galbraith and Kane (1993) observed attention-related modulation at cortical levels in a study of attentional influences on FFRs and cortical event-related potentials. They simultaneously recorded brainstem FFRs and cortical event related potentials elicited by a 230

Hz tone while participants performed a directed attention task in which the auditory stimuli were either actively attended to or deliberately ignored. The cortical ERPs demonstrated significant attentional effects, with larger responses observed for attended stimuli than for ignored stimuli, confirming the effectiveness of the attentional manipulation (Galbraith & Kane, 1993). These findings suggested that attentional modulation may be more readily reflected in cortical auditory processing than in subcortical neural responses and highlighted the importance of task demands in determining whether attentional effects extend to early stages of auditory processing (Galbraith & Kane, 1993).

Subsequent studies further explored the neural basis of attentional influence on FFRs (Hartmann & Weisz, 2019; Schüller et al., 2023). Hartmann and Weisz (2019) recorded FFRs with a whole-head MEG system while participants performed a cross-modal attention task in which they were instructed to selectively attend to either the auditory or visual modality while a repeating speech stimulus was continuously presented. They found that among all regions with measurable FFR activity, only the right primary auditory cortex showed significant modulation by attention in source-level analyses across subcortical and cortical regions of interest, while subcortical structures such as the inferior colliculus and cochlear nucleus were not affected by the attentional manipulation.

Building further on this, Schüller et al. (2023) used MEG to investigate the attentional modulation of the cortical contribution to the speech FFR, participants were presented with two competing continuous speech signals and cortical responses were analysed while the participants switched their selective attention between the two speakers. At latencies around 30 to 40 ms, the cortical part of the FFR was significantly modulated by selective attention, displaying larger neural responses when a speaker was attended than when ignored (Schüller et al., 2023). Together, these results suggest that attentional effects on the FFR are not limited to subcortical structures, but also involve cortical auditory areas, and thus highlight the

involvement of higher-order cognitive processes in the generation of the scalp-recorded response (Hartmann & Weisz, 2019; Schüller et al., 2023).

These findings are particularly relevant to the present study because the introduction of a cognitive task during FFR recording may alter the cortical state and top-down auditory modulation. Therefore, variations of amplitudes of F0, harmonics and formants across task and no-task conditions may offer indirect evidence for cortical and corticofugal influences on speech encoding.

CHAPTER 3

METHODS

The primary aim of the study was to explore effect of attention on the context dependent encoding of FFR thereby inferring on the influence of cortical regions and corticofugal pathways on the generators of FFR by employing a cognitive task engagement. Grossly, the method involved recording FFRs using repetitive and variable stimulus paradigm in conditions with and without concurrent cognitive task engagement in a group of normal hearing adults. The specific details of the method used are given in the subsequent sections.

3.1 Participants

The participants included 20 normal hearing adults aged 18 to 25 years (mean age ± SD: 21.8 ± 2.19). The group comprised 13 males and 7 females. All the participants were pursuing Bachelors or Master's Degree at the All India Institute of Speech and Hearing, Mysuru. To qualify as participants potential candidates had to have:

- Bilateral normal hearing sensitivity, with air conduction pure-tone hearing thresholds ≤15 dB HL at octave frequencies between 250 Hz and 8000 Hz.
- Type A or As tympanogram with the presence of ipsilateral acoustic reflexes at 1 kHz, indicative of normal middle-ear functioning in immittance audiometry.
- Otoacoustic emissions present in the test ear, with at least three consecutive test frequencies showing a signal-to-noise ratio of 6 dB or higher.
- Normal or corrected-to-normal vision, as assessed using Snellen's chart, tested at 6 meters from the chart.
- No past or present history of otological or neurological disorders or related complaints.

- Adequate speech perception in noise abilities, operationally defined as >60% performance at 0 dB SNR, assessed using the standardized phonemically balanced (PB) word list in the respective native language of the candidate.

3.2 Test stimuli

Four consonant-vowel (CV) syllables /bi/, /bu/, /gi/ and /da/ were used to elicit Frequency Following Responses. The syllable /da/ served as the target stimulus, while the other three syllables acted as contextual stimuli, chosen to differ in vowel, stop burst, and second formant transitions. The target stimulus /da/ was presented in the presence of contextual stimuli in the variable stimulus paradigm and was the only stimulus in the repetitive stimulus paradigm. The syllables used in Maruthy et al. (2017) were borrowed for the present study.

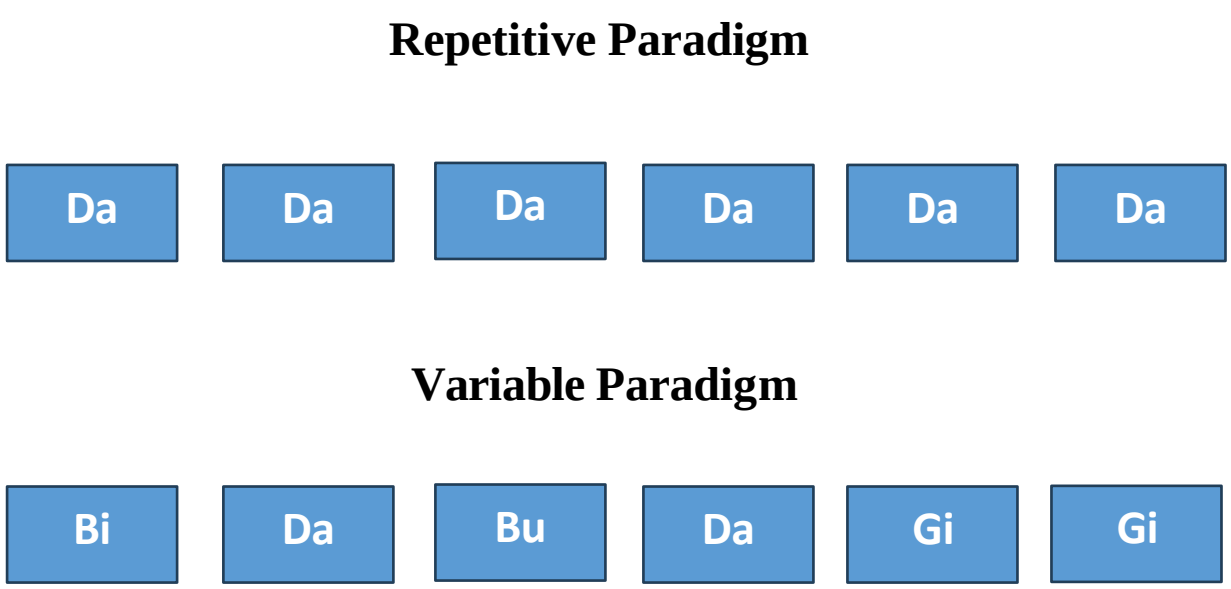

Figure 3.1: Schematic representation of the two stimulus paradigms used in the study. The upper panel shows the repetitive paradigm and the lower panel shows the variable paradigm.

The speech syllable /da/ of 100 ms duration, originally developed by M. Maruthy et al. (2017), was used in the present study. A longer stimulus duration was preferred because spectral information is represented more effectively and yields a more robust FFR compared to shorter-duration /da/ stimuli (e.g., 40 ms). The syllables were originally uttered by an adult male native speaker of Kannada and recorded using a dynamic microphone positioned approximately six inches from the speaker's mouth. The microphone output was routed to the Stim2 hardware (Compumedics-Neuroscan, Charlotte, NC, USA) and recorded at a 16-bit resolution with a sampling frequency of 44,100 Hz using the Sound module of the Stim2 software suite. The duration of the syllables was edited to 100 ms by deleting vowel cycles beyond 100 ms at the nearest zero-crossing.

The recorded syllables were analyzed using Speech Processing and Synthesis toolboxes incorporating a linear predictive coding algorithm to independently extract and modify different acoustic parameters. The modified linear predictive coding parameters were then used to synthesize the CV stimuli (/bi/, /bu/, /gi/, and /da/) of 100 ms duration. These synthetic speech syllables were subsequently subjected to perceptual rating for naturalness and quality by 10 sophisticated listeners. Based on the listeners' ratings, the linear predictive coding parameters were further modified to resynthesize stimuli with improved naturalness. The waveforms and spectrograms of the four syllables generated by Maruthy et al. (2017) and used in the present study are shown in Figure 3.2, and their spectral characteristics are presented in Table 3.1.

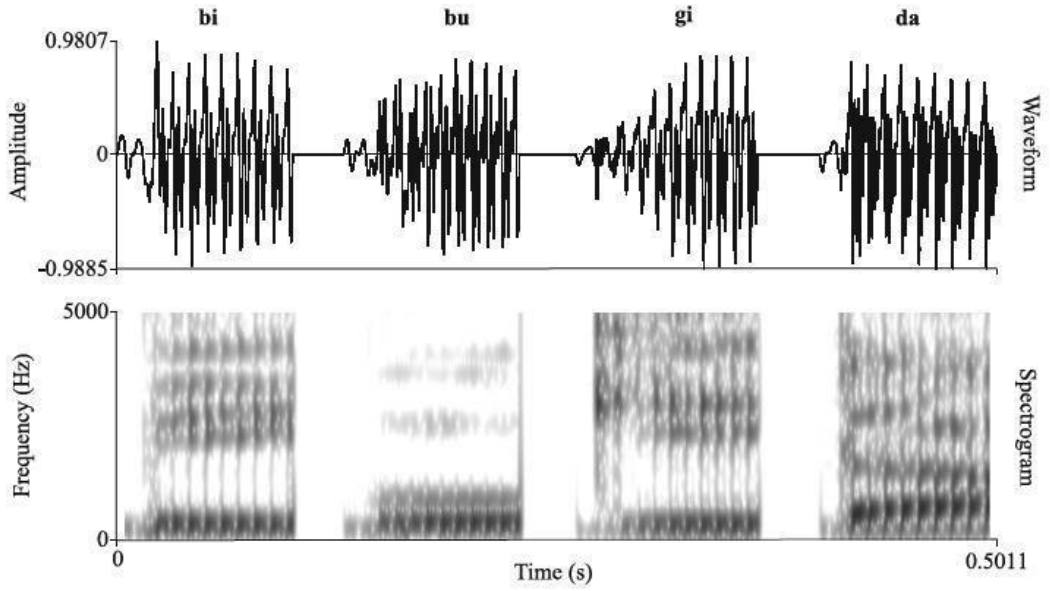

Figure 3.2: The waveforms and Spectrograms of syllables /bi/, /bu/, /gi/ and /da/, borrowed from Maruthy et al. (2017) and used in the present study.

Table 3.1: Spectral characteristics of /bi/, /bu/, /gi/ & /da/ syllables used in the present study

Stimulus	F0 (Hz)	F1 (Hz)	F2(Hz)	F3 (Hz)	F4 (Hz)	F5 (Hz)
/bi/	100.29	563 to 630	1168 to 1193	2488 to 2566	3690 to 3748	Steady 5091
/bu/	117.58	324 to 328	836 to 845	2533 to 2534	3667 to 3746	Steady 5331
/gi/	113.07	267 to 295	2213 to 2377	3042 to 3147	4049 to 4015	Steady 4846
/da/	100.24	563 to 692	1453 to 1281	2510 to 2475	3285 to 3287	Steady 3472

3.3 Test Environment

All tests were carried out in an electrically and acoustically shielded audiometric rooms wherein the ambient noise levels were well within the permissible limits prescribed by ANSI/ASA S3.1-1999 (R2013).

3.4 Instrumentation

In the present study, several technical equipment were used to conduct basic audiological assessment, and to record FFRs:

- A calibrated two-channel Inventis Piano diagnostic audiometer (Inventis, Padova, Italy) with TDH-39 supra-aural headphones was used for pure-tone audiometry, speech audiometry and Speech perception in noise test.
- A calibrated GSI TympStar Pro (Grason Stadler Inc., Minnesota) immittance meter was used to record tympanogram and acoustic reflex thresholds.
- Otoacoustic emissions were recorded using ILOV6 software (Otodynamics Audiology Systems, UK).
- A standard snellen's chart was used for the assessment of visual acuity at a distance of 6 meters.
- An Intelligent Hearing Systems SmartEP (version 5.51) evoked potential acquisition system (IHS, Miami) with impedance-matched insert receivers (Ultra-shielded ER-3A insert earphones, 300-ohm-Intelligent Hearing Systems, Florida, USA) were used for acquiring FFRs.

3.5 Test Procedure

The procedures used in the study conformed to the ethical guidelines for bio behavioral research in human participants (AIISH, 2026). The study was approved by the institutional ethical review board (Ref. No: SH/IRB/M.4/AUD.31/2025-26).

An informed consent was obtained from all the participants prior to their inclusion in the study. After obtaining the informed consent, participants were subjected to pure-tone audiometry, speech audiometry, the SPIN test, immittance testing, otoacoustic emission testing and snellen's test. Only those individuals who met the inclusion criteria outlined in Section 3.1 were subsequently recruited as participants.

3.5.1 Candidacy Assessment

The potential participants were assessed for eligibility based on the predefined inclusion and exclusion criteria. The assessment procedures included structured interview, pure tone audiometry, speech audiometry, immittance evaluation, otoacoustic emissions, SPIN test and vision test. To begin with, a structured interview was conducted prior to audiological evaluation to obtain information regarding the participants' personal details, otological and neurological history. Participants reporting any history of otological or neurological disorders were excluded from the study. Ear-specific air-conduction pure-tone hearing thresholds were obtained at octave frequencies from 250 Hz to 8 kHz using the modified Hughson and Westlake method (Carhart & Jerger, 1959).

Speech audiometry included estimating speech recognition threshold and speech identification scores. Speech recognition threshold was estimated using spondee words and the speech identification score was assessed at 40dBSL (Ref: speech recognition threshold) using the phonemically balanced word test in the respective native language of the

participants. The same audiometer used for pure-tone audiometry was also used for speech audiometry.

Admittance of the middle ear was tested for a 226Hz probe tone using Grason Stadler Inc. Tympstar immittance meter. Compensated tympanogram was recorded using a probe tone of 226Hz and by sweeping the ear canal pressure from +200 to -400 daPa. The response parameters; peak static admittance, peak pressure and ear canal volume were noted down to interpret the middle ear status. Normal functioning of middle ear was indicated by bilateral type 'A' or 'As' tympanogram with presence of ipsilateral acoustic reflexes at 1 kHz.

Distortion Product Otoacoustic Emissions were measured using pure-tone stimuli, with L1 set at 65 dB SPL and L2 at 55 dB SPL. The frequency ratio of F2 to F1 was maintained at 1.22, and F2 frequencies ranged from 1000 to 6000 Hz. Following the criteria outlined by Norton et al. (2000), OAEs were deemed present when the SNR exceeded 6 dB at three consecutive frequencies.

Speech perception in noise was assessed using the phonetically balanced (PB) word list in the respective native language. The noise detection threshold and speech detection threshold were determined using standard clinical procedures (ANSI/ASA S3.6, 2018; ISO 8253-3, 2022). Subsequently, PB words were presented at 40 dB above the speech detection threshold, while speech noise was simultaneously presented at 40 dBSL above the noise detection threshold maintaining a 0 dB signal-to-noise ratio. The participants were instructed to listen carefully to the speech stimuli presented and repeat them. The number of responses correctly identified was scored and expressed as percentage correct. Those participants who achieved a score above 60% at 0 dB SNR were considered eligible to take part in the study.

Individuals were seated at a standard distance of 6 meters from the snellen's chart. They were instructed to read the optotypes displayed on the chart with each eye separately and then

with both eyes together. Those with normal visual acuity, with or without corrective lenses, were deemed eligible for inclusion in the study.

3.5.2 Recording FFRs

The participants were seated in a sound treated and electrically shielded audiometric room. They were instructed to relax and minimize the extraneous movements of the head and neck region of the body during the recording.

Intelligent hearing systems hardware with Smart EP software (Version 5.54.21) was used to record the FFRs. The target electrode sites (nape of the neck, nasion, & Cz) were prepared using a skin preparation gel. Gold-plated electrodes were applied with conducting gel and secured in place using adhesive tape. The absolute electrode impedance at each electrode site was maintained below 5 kΩ throughout the recording. FFRs were recorded with electrodes placed in vertical montage (Positive at Cz, Negative at Nape of neck & Ground electrode at Fpz). The specific stimulus and acquisition parameters used to record the FFRs are given in Table 3.2.

Table 3.2: Stimulus and acquisition parameters used in the study to record FFRs

	Stimulus Parameters
Stimuli	Repetitive paradigm: /da/ only Variable paradigm: /da/, /bi/, /bu/, /gi/
Ear	Binaural
Duration of stimulus	100 ms
Intensity	70 dBnHL
Repetition rate	5.1/s

Polarity	Alternating Polarity
Acquisition Parameters	
No of channels	1
Analysis time	125 ms
Electrode montage	Vertical
Amplification	100000
Artifact rejection	25 µV
Filter setting	30-1500 Hz
Number of averages	1500 averages for the target stimuli

The FFRs elicited by /da/ were recorded under four experimental conditions derived from two stimulus paradigms (repetitive and variable) presented in the presence and absence of a working memory task. Responses in each condition were recorded twice to ensure waveform replicability.

In the repetitive paradigm, the /da/ stimulus was presented repeatedly, and the response was obtained by averaging across 1500 stimulus sweeps. Whereas in the variable paradigm, /da/ was presented in the context of the syllables /bi/, /bu/, and /gi/, with each syllable occurring at an equal probability of 25% and 1500 sweeps. The order of the syllables was random within the variable paradigm. FFRs in both paradigms were recorded with and without the concurrent working memory task involving simple arithmetic calculations. The arithmetic calculations were presented visually on a computer screen positioned at a comfortable viewing distance in front of the participant. Simple addition and subtraction problems with a designated correct or incorrect answer were displayed on the screen (4+3=8,

[incorrect]; 5+2=7 [correct]). The purpose of incorporating the working memory task is to divert the participant attention away from the auditory stimuli and to engage higher order cortical processes such as attention and working memory, thereby examining there influence on auditory neural encoding. During the recording, arithmetic calculations with correct and incorrect answers were presented, and participants were explicitly instructed to carefully read each arithmetic problem displayed on the screen, mentally solve the calculation, and raise their index finger whenever the displayed answer was correct. The examiner, who was seated outside the sound treated booth, monitored the participant through the observation window, visually tracked and manually recorded each finger raising response. They were instructed to minimize movement artifacts by remaining as still as possible while performing the task and to continue attending to the screen throughout the recording. Response accuracy during the working memory task was monitored to ensure active participation and task engagement throughout the recording. A minimum accuracy of 70% correct response was considered as indicative of adequate task performance, based on performance criteria commonly employed in adaptive working memory paradigms (Gudi-Mindermann et al., 2020).

The selected criterion ensured that participants were actively performing the working memory task during FFR recording rather than responding randomly or inattentively. Participants who did not achieve this level of accuracy in any condition were excluded from the corresponding analysis to avoid inclusion of recordings obtained under reduced attention or poor task engagement.

The entire data collection procedure for each participant was completed across two separate sessions conducted on different days to minimize participant fatigue and maintain the quality of the recordings. The candidacy assessment (otoscopic examination, pure-tone audiometry, immittance audiometry, SPIN test, OAE, snellen’s test) was done at the first

session, followed by electrode preparation and recording of FFRs in the second session conducted on a different day. The total duration of the recording procedure was approximately 90 to 120 minutes in total, and short breaks of approximately 5 to 10 minutes were provided between conditions whenever required to reduce fatigue, maintain participant comfort and minimize movement related artifacts during FFR recordings. The four experimental conditions were randomized across participants to control for order and practice effects.

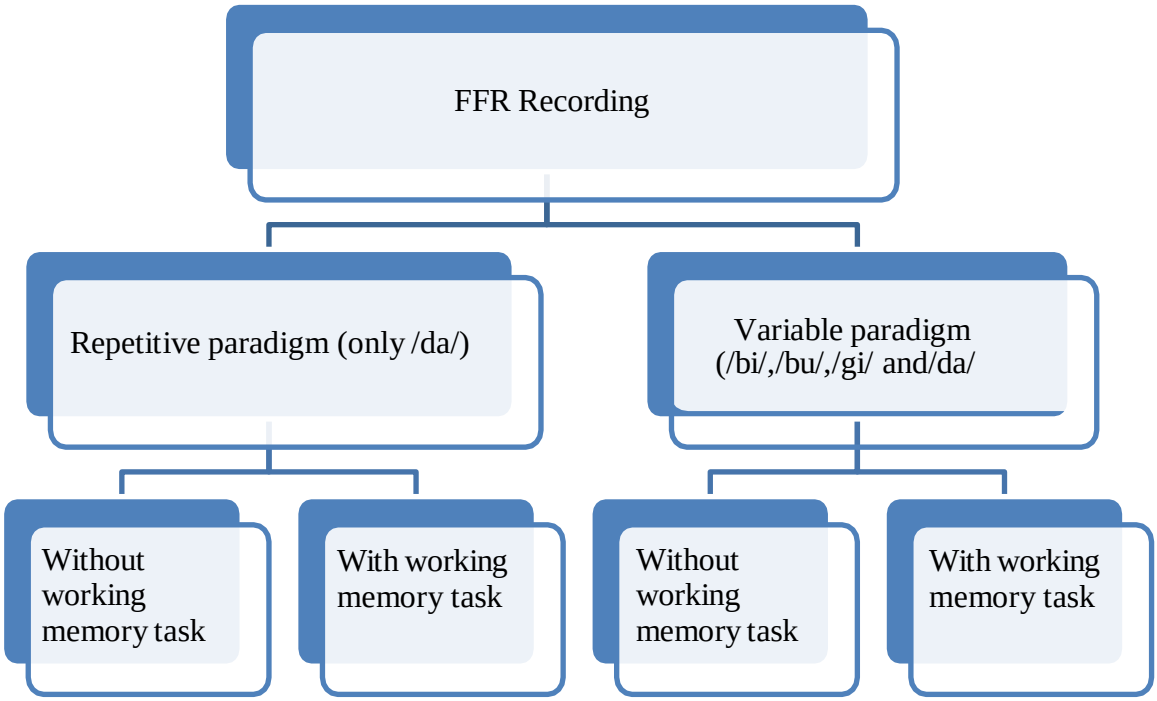

Figure 3.3: Representation of different experimental conditions used in the present study.

3.5.3 Response Analysis

The averaged response obtained for syllable /da/ in the four stimulus conditions were objectively analysed using Fast Fourier Transform (FFT). This was to derive the spectral composition of the response in its sustained portion (FFRs). FFT analysis was performed over the latency range of -64 to 53ms corresponding to the recorded response window containing the sustained phase locked neural activity of the stimulus. Spectral analysis was performed to obtain the amplitudes of fundamental frequency (F0-100 Hz), second harmonic (H2 - 200 Hz), third harmonic (H3 - 300 Hz), fourth harmonic (H4=400) and the first formant frequency (F1-617). FFR recordings 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: Envelope (FFR_{ENV}) - by summing the two polarity FFR, and Temporal Fine Structure (FFR_{TFS}) - by subtracting one polarity FFR from the other.

The F0 and the harmonic amplitudes were extracted from the envelope component of the FFR (FFR_{ENV}), whereas the F1 amplitude was extracted from the temporal fine structure component of the FFR (FFR_{TFS}). This was done in a custom written program in Matlab R2023b platform developed at Northwestern University. The recordings were subjected to offline filtering with two different filter settings as a function of the component of interest. A band pass filter of 30-800 Hz was used for envelope analysis and a filter of 100-2000 was used for Temporal fine structure analysis.

The raw amplitude value of the F0, H2, H3, H4 and F1 of the FFR was then measured. The waveforms were windowed from -64 to 53ms using a 10% tapered Tukey window and zero-padded up to a total duration of 1 s to increase the spectral resolution to 1Hz. The zero-padded waveforms were then subjected to FFT. The magnitudes at F0, H2, H3, H4 and F1 were

then analyzed by averaging the magnitudes of ten bins (1 Hz wide) around the F0, H2, H3, H4 and F1 frequencies. These spectral magnitudes were used as the index of brainstem encoding for both EFRs and FFRs.

The data thus obtained were used for the comparison of FFR recorded in repetitive and variable stimulus paradigms, with and without the working memory task. The difference between the repetitive and variable paradigms was considered as the index of context-dependent encoding, and the derived measures were compared across the task conditions to verify the objectives of the study.

3.6 Data Analysis

Data were entered into an Excel spreadsheet, and the accuracy of the entries was verified prior to analysis. The data were then imported into IBM SPSS Statistics (version 21) for further analysis. The statistical significance of the FFR measures in the four stimulus conditions were analysed. Group data were examined to calculate the mean, and standard deviation of the F0, H2, H3, H4 and F1 amplitudes.

To achieve the objectives of the study, the inferential statistical analyses such as repeated measures ANOVA were performed. First, to evaluate the effect of cognitive task engagement on FFRs, amplitudes recorded in task and no-task conditions were compared separately for the repetitive and variable stimulus paradigms. Second, to assess the impact of stimulus paradigm, FFR spectral amplitudes obtained under the repetitive paradigm were compared to FFR amplitudes obtained under the variable paradigm, separately for task and no-task conditions. Third, to evaluate the effect of cognitive task engagement on context-dependent encoding, the difference between FFR amplitudes obtained with the repetitive and variable stimulus paradigms was calculated as an index of context-dependent encoding and compared between task and no-task conditions. The level of statistical significance was set at $p < 0.05$ for all analyses.

CHAPTER 4

RESULTS

The present study aimed to investigate the effect of attention on the context-dependent encoding of the frequency-following responses (FFRs) by employing cognitive task engagement. This approach was used to infer the influence of cortical regions and corticofugal pathways on the generation of the FFR. Figure 4.1 shows a representative set of FFR waveforms recorded in an individual participant in the repetitive stimulus paradigm, without and with cognitive engagement task. Similarly, Figure 4.2 shows the FFRs recorded in the variable stimulus paradigm.

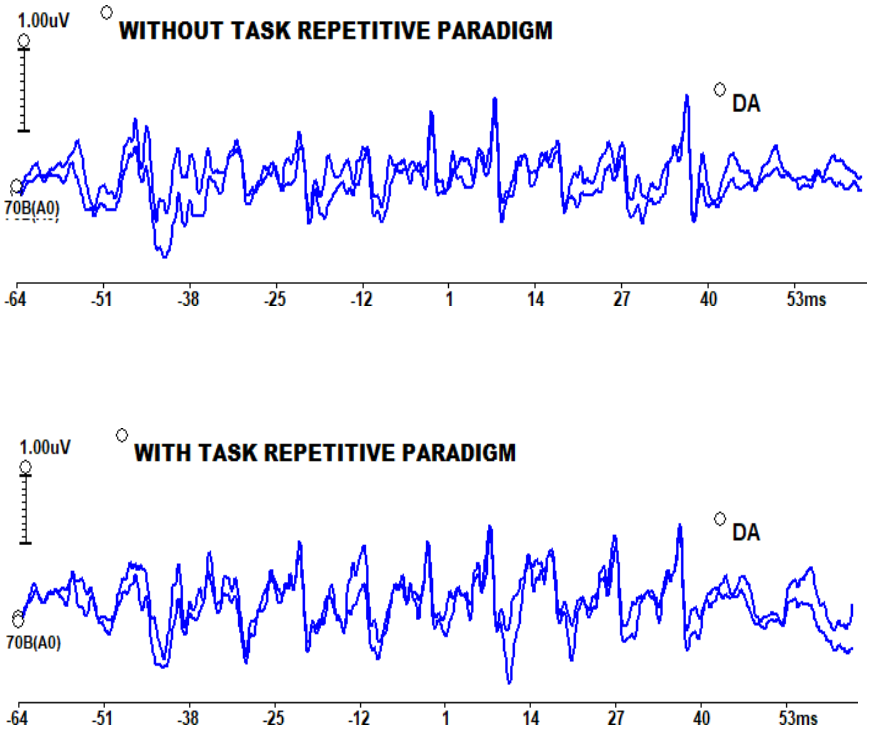

Figure 4.1: A representative set of waveforms recorded in an individual participant in the repetitive stimulus paradigm without and with cognitive task engagement.

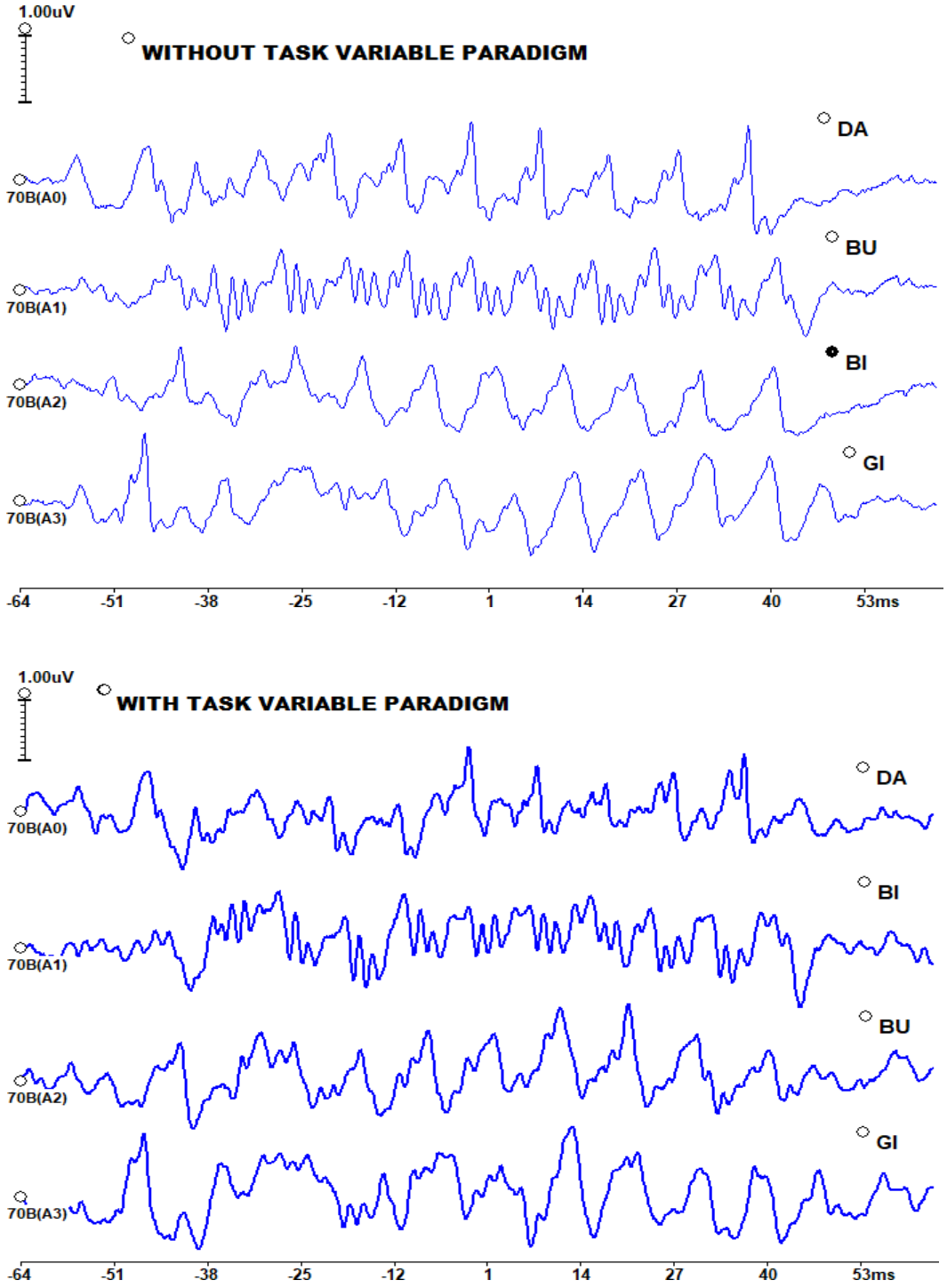

Figure 4.2: A representative set of waveforms recorded in an individual participant in variable stimulus paradigm without and with cognitive task engagement.

Figure 4.3 shows the grand average spectra of the Envelope following responses (EFRs) obtained in repetitive stimulus paradigm, without and with a cognitive task engagement. F0, H2, H3 and H4 were derived from the individual EFR spectrum. F0 and H2 appeared higher in amplitude in the with-cognitive task recordings compared to the without, in the grand average spectra.

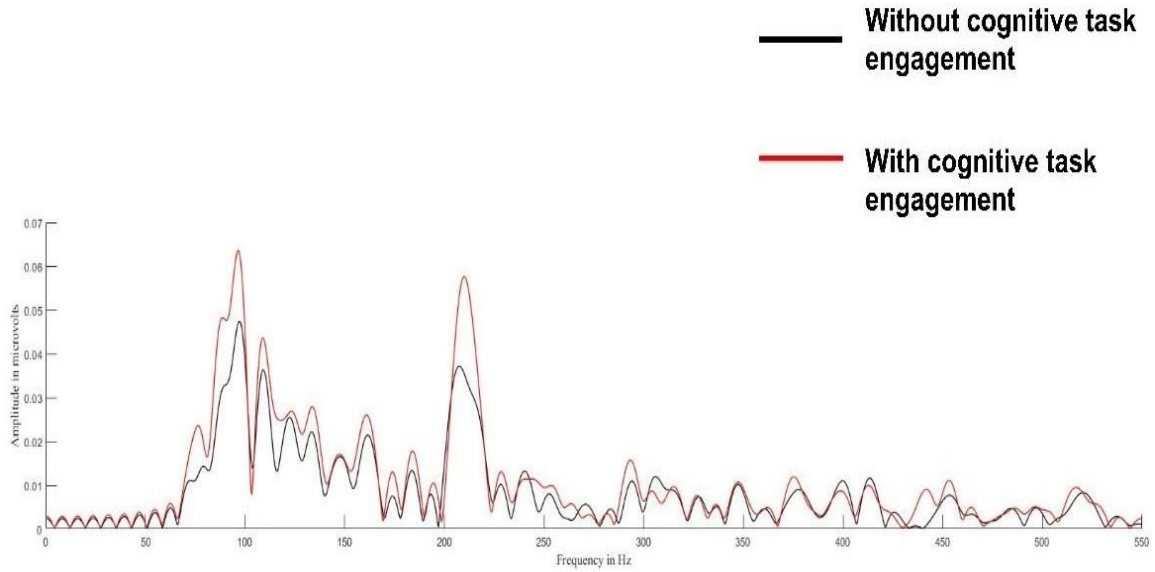

Figure 4.3: The grand average spectra of EFR in the repetitive paradigm, without and with cognitive task engagement.

Figure 4.4 shows the grand average spectra of the FFR fine structure obtained in the repetitive stimulus paradigm, with and without cognitive task engagement. The amplitude of F1 was derived from the individual FFR fine structure spectrum. No evident differences could be observed in the F1 between without and with cognitive task.

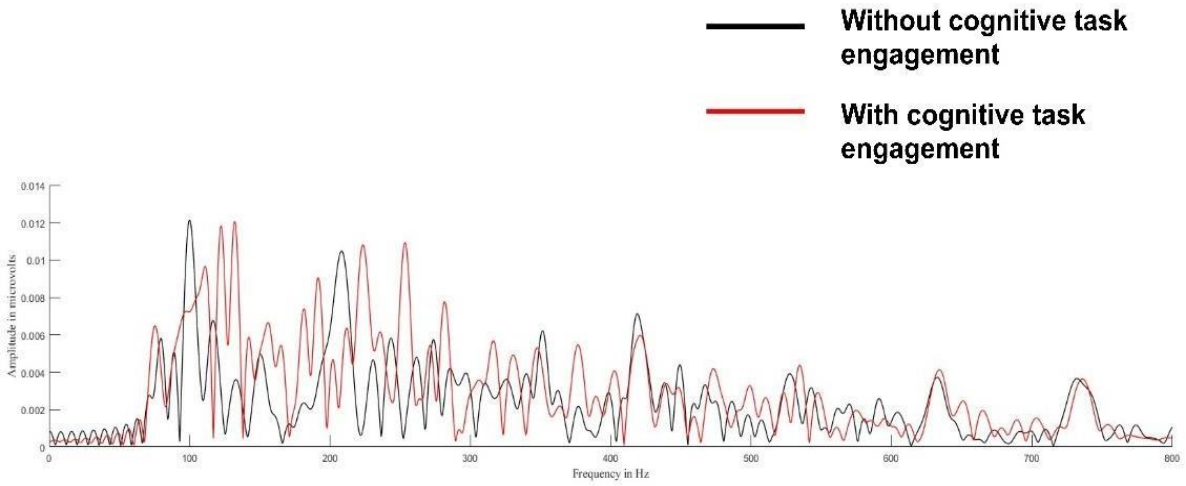

Figure 4.4: The grand average spectra of FFR fine structure recorded using the repetitive paradigm, with and without cognitive task engagement.

Figure 4.5 shows the grand average spectra of the EFRs obtained in variable stimulus paradigm, without and with cognitive task engagement. No consistent pattern of differences could be observed between the two conditions in the grand average spectra.

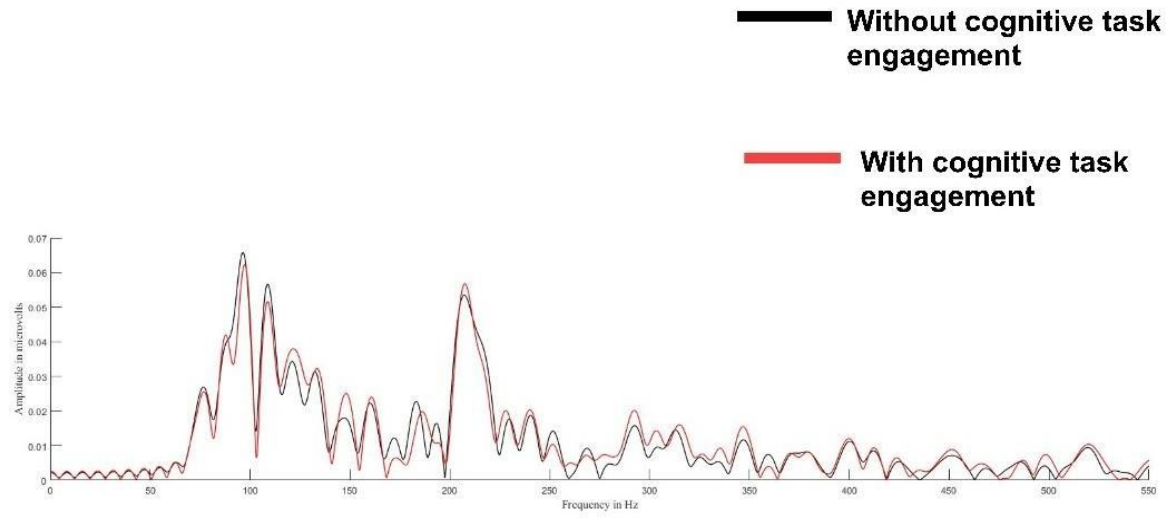

Figure 4.5: The grand average spectra of EFRs recorded using the variable stimulus paradigm, with and without cognitive task engagement.

Figure 4.6 shows the grand average spectra of the FFR fine structure obtained in the variable stimulus paradigm, without and with cognitive task engagement. F1 region showed higher amplitude in the without cognitive task engagement condition than that of the with cognitive task.

Figure 4.6: The grand average spectra of FFR fine structure in the variable paradigm, with and without cognitive task engagement.

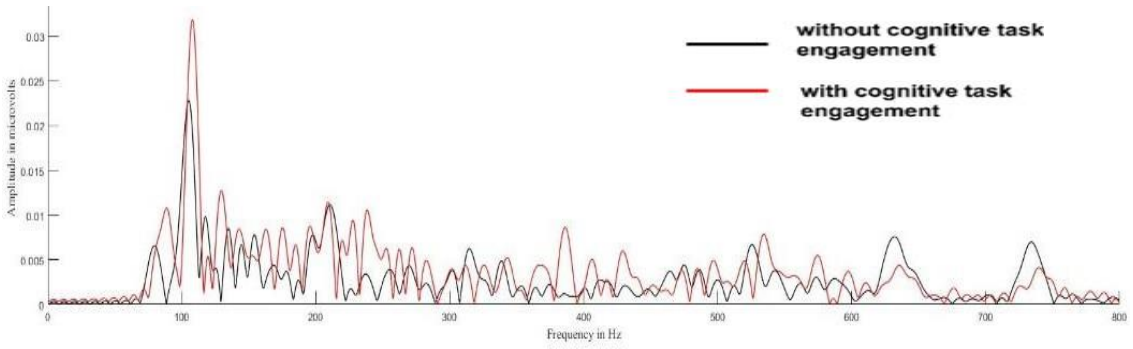

Figure 4.7 shows the grand average spectra of the EFR obtained in repetitive and variable stimulus paradigms, without the cognitive task engagement. The amplitude of F0 and H2 appeared higher in the variable paradigm compared to that in repetitive paradigm.

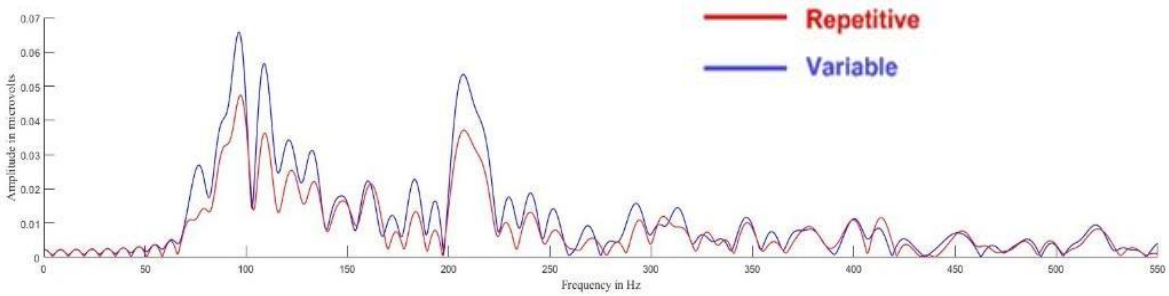

Figure 4.7: The grand average spectra of EFR recorded using variable and repetitive paradigm in without cognitive task engagement condition.

Figure 4.8 shows the grand average spectra of the FFR fine structure obtained in repetitive and variable stimulus paradigms, without the cognitive task engagement. The F1 region showed higher amplitude in the variable paradigm compared to the repetitive paradigm.

Figure 4.8: The grand average spectra of FFR fine structure in the variable and repetitive stimulus paradigms, without cognitive task engagement.

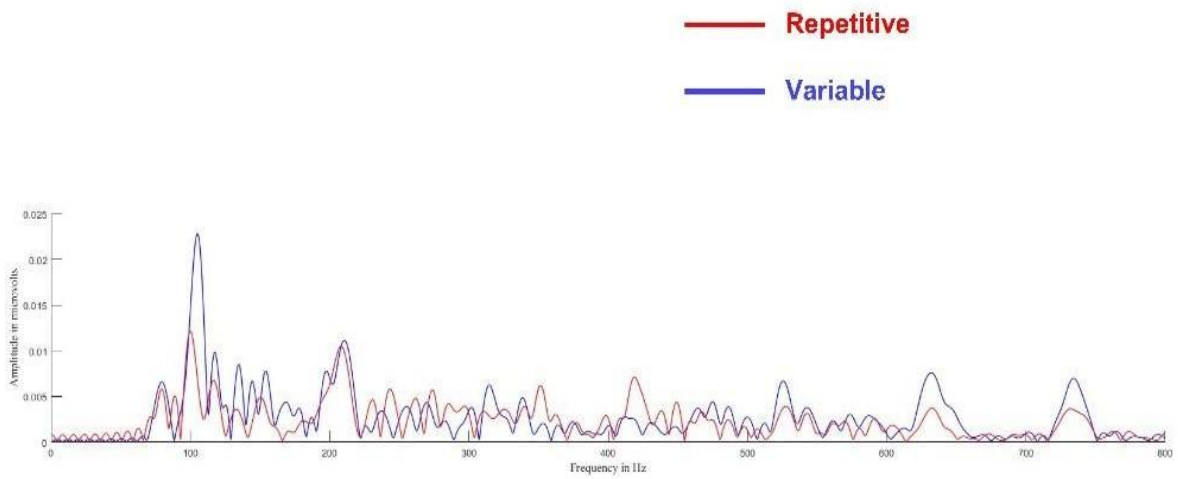

Figure 4.9 shows the grand average spectra of the EFR obtained in repetitive and variable stimulus paradigms, with the cognitive task engagement. The F0 region showed higher amplitude in the variable paradigm compared to the repetitive paradigm. H2 spectral peak appeared to be larger in repetitive paradigm compared to variable paradigm. The H3, H4 and F1 regions exhibited comparable amplitudes between the two paradigms.

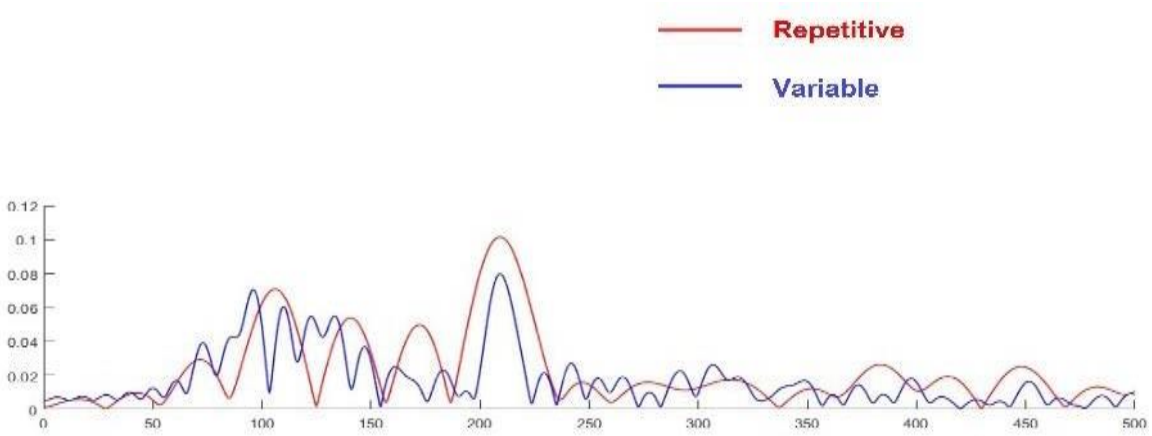

Figure 4.9: The grand average spectra of EFR in repetitive and variable paradigms in the with- cognitive task engagement condition.

Figure 4.10 shows the grand average spectra of the FFR fine structure obtained in repetitive and variable stimulus paradigms, with the cognitive task engagement. No evident differences could be observed in the F1 between repetitive and variable paradigms in the presence of cognitive task engagement.

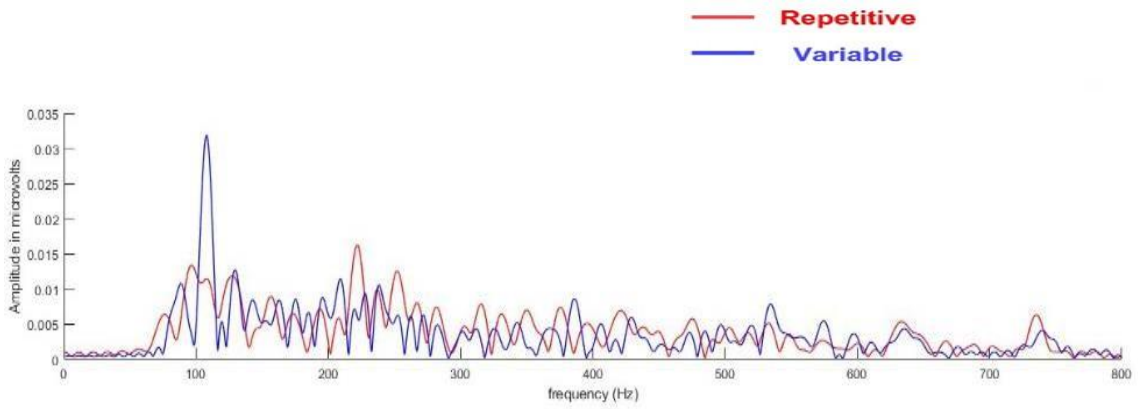

Figure 4.10: The grand average spectra of FFR fine structure in the repetitive and variable stimulus paradigms, with-cognitive task engagement.

The group data was tested for its type of distribution using Shapiro Wilk's test of normality. The results revealed that the majority of the variables were normally distributed ($p > 0.05$), satisfying the assumption for the use of parametric statistical tests. Accordingly, parametric tests were employed for further analysis. The results obtained in the present study are reported under the following headings:

1. Effect of cognitive task engagement and stimulus paradigm on FFR
2. Effect of cognitive task engagement on the context dependent encoding of FFR.

4.1 Effect of Cognitive Task Engagement and Stimulus Paradigm on FFR

Table 4.1 presents the mean and standard deviation of F0, H2, H3, H4, and F1 amplitudes between the two stimulus paradigms (repetitive & variable) and the two task conditions (with & without cognitive task engagement). Inspection of the descriptive statistics revealed variations in the mean spectral amplitudes across the different experimental conditions.

The effects of stimulus paradigm and cognitive task engagement on spectral amplitudes were statistically evaluated using a repeated-measures ANOVA (Table 4.2). The results revealed no significant main effect of stimulus paradigm on the amplitudes of F0, H2, H3, H4, and F1. However, a significant main effect of task was observed for H2 and H3 amplitudes, with large effect sizes ($\eta p^2 > 0.3$), whereas no such significant effects were found for F0, H4, or F1. Both H2 and H3 amplitudes were higher during cognitive task engagement than in the absence of cognitive task engagement.

Table 4.1: Mean and standard deviation of F0, H2, H3, H4 and F1 in the two paradigms (repetitive & variable), in the two task conditions (with and without cognitive task engagement)

Measure	Paradigm	With cognitive task		Without cognitive task	
		Mean (µV)	**SD**	**Mean (µV)**	**SD**
F0	Repetitive	0.081	0.031	0.081	0.040
	Variable	0.099	0.034	0.082	0.039
H2	Repetitive	0.074	0.027	0.061	0.024
	Variable	0.077	0.023	0.068	0.026
H3	Repetitive	0.033	0.015	0.027	0.011
	Variable	0.033	0.015	0.026	0.011
H4	Repetitive	0.029	0.010	0.024	0.012
	Variable	0.028	0.013	0.026	0.012
F1	Repetitive	0.026	0.013	0.028	0.014
	Variable	0.026	0.010	0.026	0.012

Although a significant interaction between stimulus paradigm and task engagement was observed for F0 amplitude, neither stimulus paradigm nor task engagement demonstrated a significant main effect. Therefore, further analysis of F0 amplitude was not pursued. Additionally, no significant interaction effects were observed for the amplitudes of H2, H3, H4, or F1.

Table 4.2: Results of repeated measures ANOVA showing the effect of stimulus paradigm and cognitive task engagement on the amplitudes of F0, H2, H3, H4 and F1 of FFRs.

Variable	Measure	F	df (error)	p	Effect Size Np^2
Paradigm	F0	3.175	1(19)	0.091	-
	H2	3.794	1(19)	0.066	-
	H3	0.002	1(19)	0.961	-
	H4	0.316	1(19)	0.581	-
	F1	0.709	1(19)	0.410	-
Cognitive task	F0	1.947	1(19)	0.179	-
	H2	10.399	1(19)	0.004*	0.354
	H3	10.028	1(19)	0.005*	0.345
	H4	2.637	1(19)	0.121	-
	F1	0.177	1(19)	0.679	-
Paradigm* Cognitive task Interaction	F0	7.121	1(19)	0.015*	0.273
	H2	0.459	1(19)	0.506	-
	H3	0.076	1(19)	0.786	-
	H4	0.550	1(19)	0.467	-
	F1	0.000	1(19)	0.990	-

Figure 4.11 shows the individual amplitudes of H2 and H3 across the four conditions: repetitive without task (RS), repetitive with task (RT), variable without task (VS), and variable with task (VT). In H2, 13 of 20 participants had higher amplitudes in the RT condition than in the RS condition, and 15 of 20 participants had higher amplitudes in the VT condition than in the VS condition. For H3, higher amplitudes were observed in 12 of 20 participants in the RT

condition compared to the RS condition, and in 13 of 20 participants in the VT condition compared to the VS condition. However, substantial inter-subject variability and overlap among conditions were evident for both H2 and H3 amplitudes.

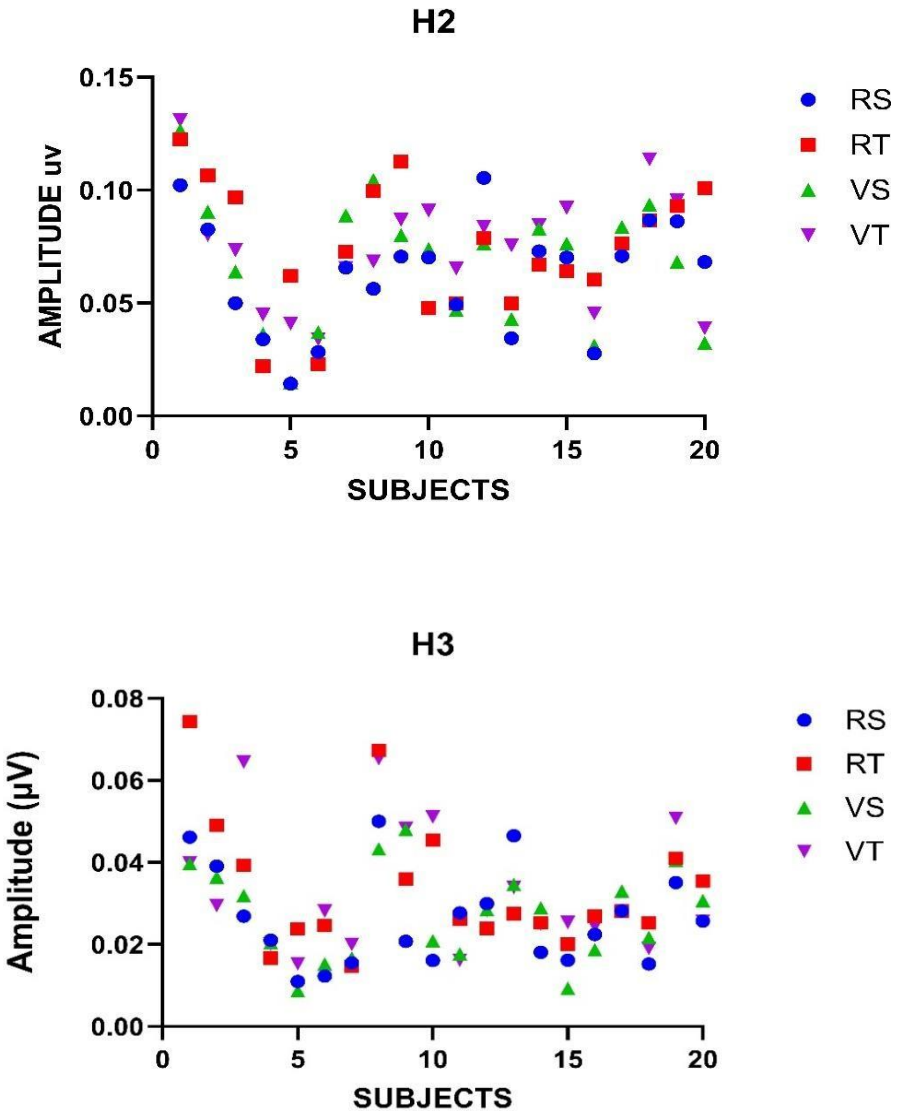

*Figure 4.11: Individual amplitudes of H2, H3 across the four conditions (2 stimulus paradigms*2 task conditions)-Repetitive without task (♦), repetitive task (■), variable without task (▲) and variable with task (▼).*

4.2 Effect of Cognitive task on Context Dependent Encoding of FFR

Context dependent brainstem encoding at F0, H2, H3, H4 and F1 were derived by subtracting the amplitude of variable paradigm from that of repetitive paradigm. This was done separately for the data of the two stimulus paradigms and the two task conditions. The obtained data did not show a consistent pattern of context dependent encoding across the measured FFR components in either of the conditions. Majority of the measures did not reveal significant differences between the repetitive and variable stimulus paradigms, indicating that a clear effect of context dependent encoding could not be established in the present test conditions.

The figures show that for most of the participants, the difference between the repetitive and variable stimulus paradigms was absent. Although a few participants showed relatively higher positive amplitudes suggestive of context dependent enhancement, such a pattern was observed only in a limited number of participants and was not consistently present across all participants.

Further, a few participants also demonstrated negative amplitude differences, reflecting an absence of a consistent direction of context dependent encoding across the recording conditions. Overall, the data did not show a clear robust pattern of context dependent encoding under either without task or with cognitive task engagement conditions. Hence, the statistical analysis to verify the 2nd objective of the study was not pursued.

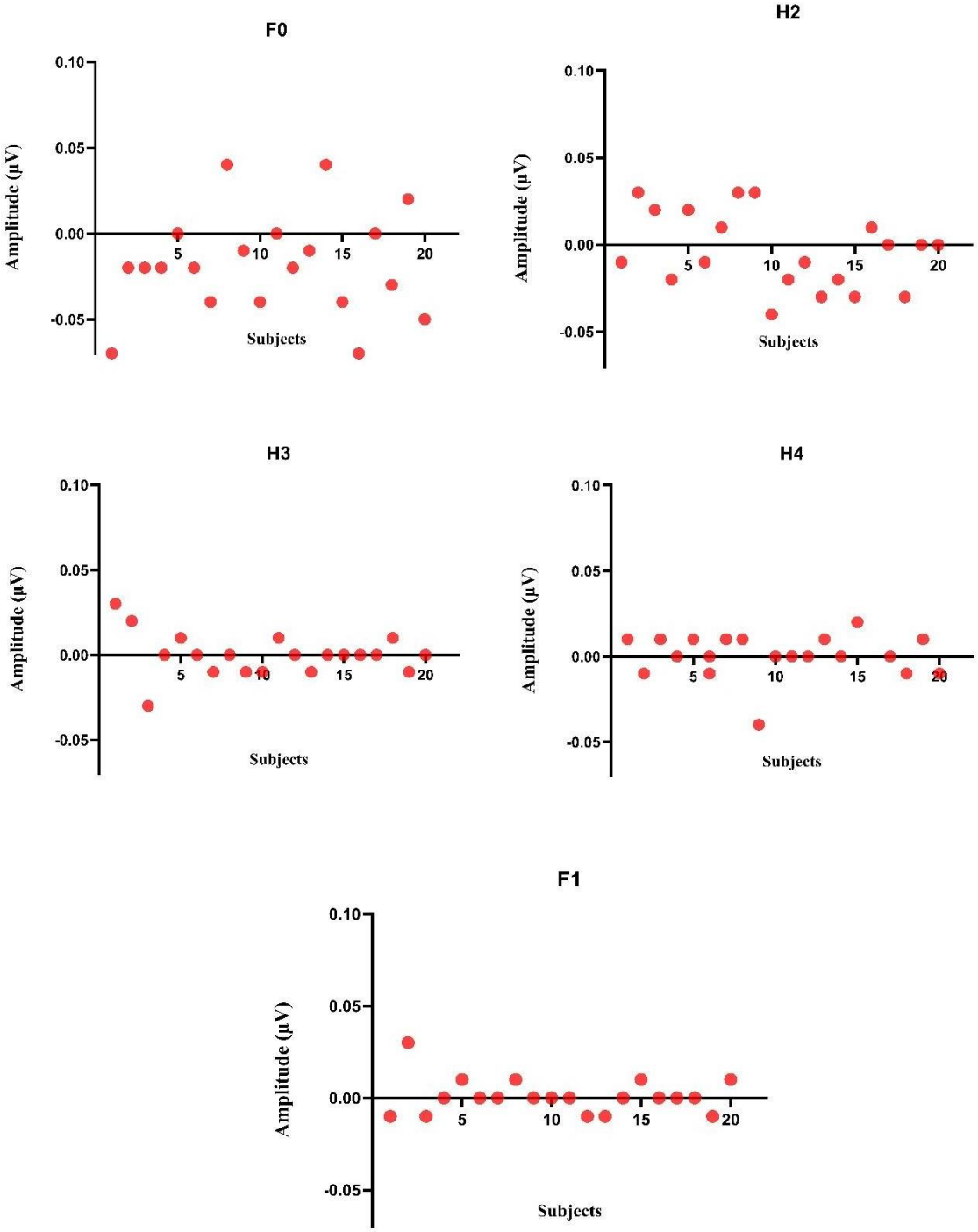

Figure 4.12: Individual data of context dependent encoding index obtained under the cognitive task engagement condition for F0, H2, H3, H4 and F1.

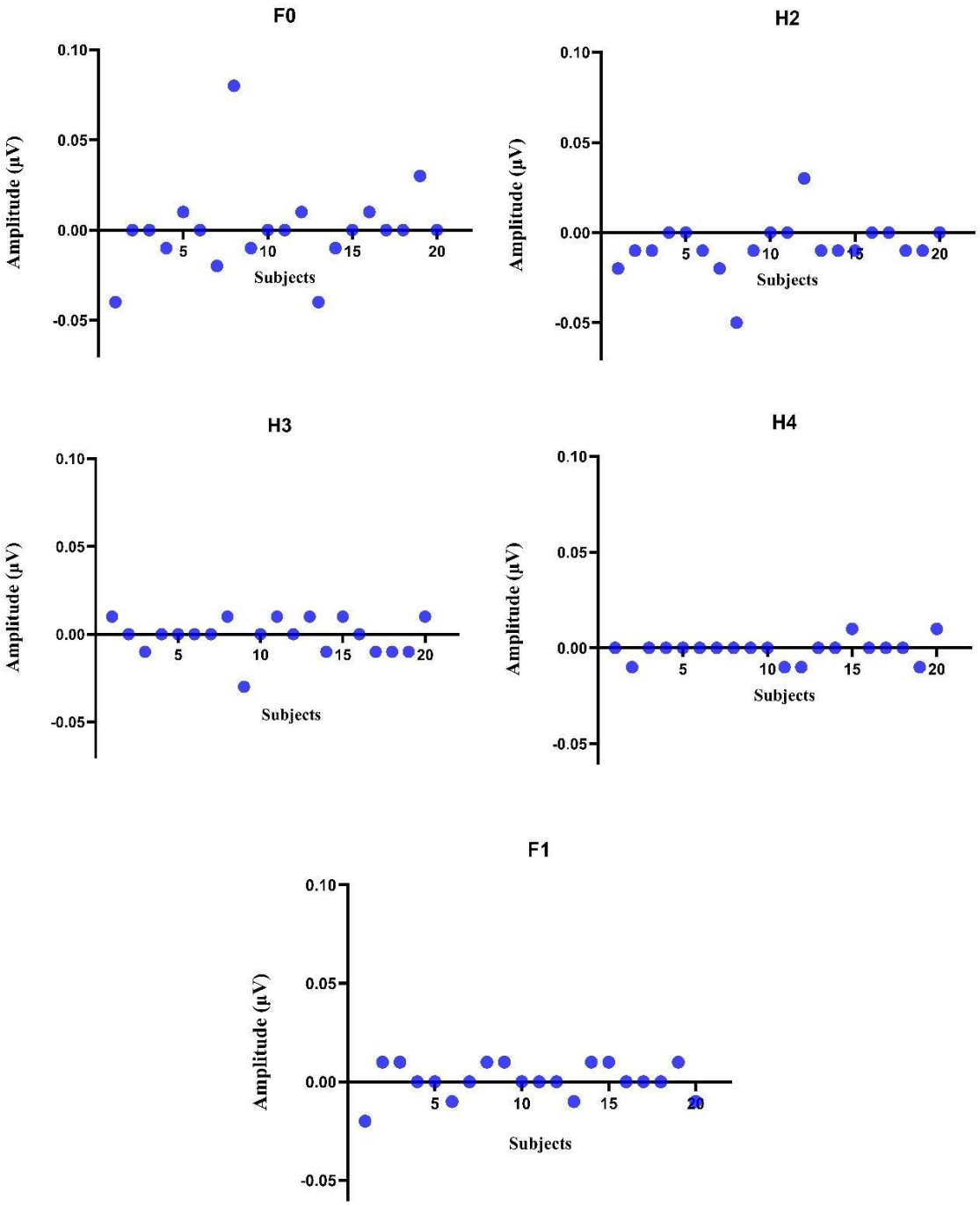

Figure 4.13: Individual data of context dependent encoding index obtained under the no cognitive task engagement for F0, H2, H3, H4 and F1.

CHAPTER 5

DISCUSSION

The primary aim of the study was to explore the effect of attention on the context dependent encoding of Frequency Following Response thereby inferring on the influence of cortical areas and corticofugal pathways on the generators of FFR by employing cognitive task engagement. Spectral analysis was carried out to analyze brainstem encoding of speech at the frequencies corresponding to the fundamental frequency (F0), higher harmonics (H2, H3 & H4) and first formants (F1) of an 100 ms /da/ syllable. This was performed in the repetitive and variable paradigm with and without a cognitive task engagement. The results showed a significant effect of cognitive task engagement on the amplitudes of H2 and H3, but no significant effect of the stimulus paradigm on any of the FFR components recorded. Moreover, a strong context-dependent encoding effect could not be observed either in the cognitive or no-task conditions. The present findings are discussed in the context of previous literature on context-dependent encoding, attentional modulation of auditory processing, and cortical contributions to the FFR. In the results of this study we found some interesting findings which are discussed under the following headings.

1. Effect of stimulus paradigm on FFR
2. Effect of cognitive task engagement on FFR
3. Effect of cognitive task on context dependent encoding
4. Implications to cortical contributions to FFR

5.1 Effect of Stimulus Paradigm on FFR

The present study investigated the influence of stimulus paradigm on FFR amplitudes by comparing the repetitive and variable stimulus conditions. Based on previous findings, it

was expected that the repetitive stimulus paradigm would elicit stronger neural encoding of speech compared to the variable stimulus paradigm. This expectation was based on studies demonstrating that repeated presentation of speech stimuli enhances the neural representation of pitch related and spectral cues in the FFR (Chandrasekaran et al., 2009; Maruthy et al., 2017). Chandrasekaran et al. (2009) reported enhanced pitch representation of the speech syllable /da/ in a repetitive paradigm and suggested that such enhancement may reflect corticofugal modulation of subcortical auditory processing. Similarly, Maruthy et al. (2017), using the same speech stimuli and paradigms employed in the present study, reported significantly greater F0 amplitudes in the repetitive paradigm compared to the variable paradigm. Therefore, stronger encoding of F0, harmonics and formant related cues was expected in the repetitive paradigm relative to the variable paradigm.

However, in the present study, no significant main effect of stimulus paradigm was found on F0, H2, H3, H4, or F1 amplitudes. Thus, the neural encoding of speech was comparable for the repetitive and variable paradigms. The comparison of repetitive and variable stimulus paradigms was based on the idea of context-dependent encoding. Context-dependent encoding refers to the improved neural representation of a speech stimulus when presented in a repetitive context relative to when the same stimulus is presented in a variable stimulus context and reflects stimulus regularity effects on auditory neural encoding (Chandrasekaran et al., 2009; Skoe & Kraus, 2010).

Chandrasekaran et al. (2009) found a significant enhancement in the F0 encoding for the speech syllable /da/ when it was presented repeatedly and suggested that this enhancement may reflect corticofugal modulation of subcortical auditory processing. Similarly, Skoe and Kraus (2010) found that the auditory system utilizes regularities in the stimulus to enhance the neural representation of acoustically relevant cues. Maruthy et al. (2017) further demonstrated

that stronger context-dependent encoding was related to better speech perception in noise performance, indicating a functional role of this phenomenon in daily listening. However, the present study did not show significant differences between the repetitive and variable paradigms, which contradicts with the findings of Chandrasekaran et al. (2009) and Maruthy et al. (2017). The descriptive statistics indicated slightly greater amplitude for some FFR parameters (e.g., F0 & H2) in the variable compared to the repetitive paradigm, but this was not uniform across all parameters and was not statistically significant.

Thus, the observed differences are probably due to the normal inter-subject variability and not to the regularity of the stimulus. A lack of paradigm effect indicates that contextual enhancement of speech encoding was not well elicited under the conditions of the present experiment. The lack of a notable paradigm effect suggests that the current experimental condition probably did not induce a strong context-dependent boost to speech encoding.

One reason could be that a cognitive task was introduced during the recording procedure. Previous studies investigating context dependent encoding have primarily examined the effect of stimulus regularity in the absence of an additional cognitive task. For Instance, Chandrasekaran et al. (2009) and Maruthy et al. (2017) recorded FFRs while participants passively listened to repetitive and variable speech stimuli, thereby allowing the effect of stimulus regularity on neural encoding to be examined without the influence of concurrent cognitive demands. In the current experiment, the cognitive task could have altered the allocation of attention and the neural resources involved in the processing of stimulus regularity, thereby diminishing the magnitude of context-dependent effects.

Another possibility is that differences in characteristics between the present study and earlier studies contributed to the divergence in findings. While Chandrasekaran et al. (2009) studied school aged children, this alone cannot fully account for the absence of context

dependent effect in the present study, whereas Maruthy et al. (2017) also employed normal hearing adults and reported significant enhancement of F0 amplitude in the repetitive paradigm relative to the variable paradigm. Thus, the variations in conclusions between studies could have been due to other factors in addition to the characteristics of the participants, such as different experimental designs and recording methods.

Another methodological difference between the present study and previous investigations relates to the recording systems employed. Chandrasekaran et al. (2009) and Maruthy et al. (2017) recorded FFRs using custom built, research grade electrophysiological acquisition systems operating at high sampling rates and optimized for detailed spectral analysis of speech evoked responses. In contrast, the present study employed a clinical evoked potential system (IHS SmartEP), which is primarily designed for clinical auditory evoked potential assessment. operates at lower sampling rate. Chandrasekaran et al. (2009) and Maruthy et al. (2017) reported clear enhancement of F0 encoding in the repetitive paradigm, whereas the present study did not demonstrate a significant difference between paradigms. Although the IHS SmartEP has been successfully used for FFR recording, differences in amplifier characteristics, sampling rate, signal processing algorithms and acquisition parameters between clinical and research grade systems may influence the magnitude and detectability of spectral components of the FFR. Skoe and Kraus (2010), noted the recording parameters such as sampling rate, amplifier sensitivity, and filter settings can affect FFR amplitudes, particularly for harmonic components.

Therefore, findings in the present study suggest that stimulus regularity alone did not have a significant impact on the encoding of F0, harmonics, and formants related components of the FFR. In contrast to earlier studies that have shown improved neural encoding in repetitive

stimulus contexts, the current study did not show strong context-dependent encoding, indicating that the effect may be influenced by task requirements and experimental settings.

5.2 Effect of Cognitive Task on FFR

The present study investigated the effect of cognitive task engagement on the neural encoding of speech as reflected by the FFR. In terms of cognitive task engagement, results indicated a significant main effect on the amplitudes of H2 and H3, with significantly higher amplitudes in the cognitive task condition compared to the no-task condition. In contrast, no significant effect of cognitive task engagement for F0, H4 and F1 amplitudes was found. Moreover, the effect of cognitive task engagement was seen regardless of stimulus paradigm, since no significant interaction between task and paradigm was found for H2 and H3. Increase in H2 and H3 amplitude in cognitive task engagement could indicate that these harmonic components reflect higher order cognitive processes during neural encoding of auditory stimuli.

The FFR is typically considered to be a subcortical response originating from the auditory nerve and brainstem nuclei, notably in the inferior colliculus (Smith et al., 1975; Greenberg et al., 1981; Marsh et al., 1974). But many studies have shown that scalp-recorded FFRs also include inputs from cortical auditory areas, and can thus be affected by attentional and cognitive factors (Coffey et al., 2016; Coffey et al., 2017; Gnanateja et al., 2021).

The present study's results are consistent with recent evidence that attentional state and cognitive engagement affects auditory neural processing (Coffey et al., 2016; Gnanateja et al., 2021; Hairston et al., 2013; Hartmann & Weisz, 2019). Hartmann & Weisz, (2019), found that in a cross-modal attention task, using magnetoencephalography of all regions exhibiting a measurable FFR response, only the right auditory cortex showed significant attentional modulation of FFR strength at the fundamental frequency, while the subcortical structures

showed relatively little modulation. The results suggested that attentional effects on the scalp-recorded FFRs might be mainly from the auditory cortex. Likewise, Coffey et al.(2016) found that FFR acquired from the scalp had significant contributions from the cortex, and suggested that the FFR was a representation of an integrated neural activity coming from both subcortical and cortical auditory structures.

The present study hypothesized that if cognitive task engagement significantly modulates the FFR, it would serve as indirect evidence for top-down cortical contributions to the FFR via corticofugal pathways. The results partially supported this hypothesis. Specifically, the increase in H2 and H3 amplitudes in cognitive task engagement compared to the no task condition, with large effect sizes, indicating that these harmonics components are susceptible to top-down modulation by higher cortical process. This is consistent with corticofugal model (Chandrasekaran & Kraus, 2010; Suga & Ma, 2003), proposes that the neural encoding in subcortical auditory structures can be modulated by descending pathways that project from the cortical auditory areas to the inferior colliculus and other brainstem nuclei.

Focusing on a cognitive task could be used to recruit more attentional resources which could improve neural synchrony for specific parts of the stimulus through corticofugal modulation. Therefore, the amplitudes of H2 and H3 were enhanced in the present study, which could also be indirect evidence of the cortical influences on the neural generators associated with the FFR. Interestingly, the cognitive task engagement induced effects were only detected with the amplitude of H2 and H3, and not with that of F0, H4, and F1. The finding indicates that various aspects of the FFR might be differentially affected by cognitive task engagement. Support for the differential effects on different harmaonics can be drawn from Gnanateja and Maruthy (2019). Also, harmonic components, like H2 and H3, which carry information beyond the fundamental frequency, may be more sensitive to top-down modulation than F0.Absence

of significant effects on F1, further indicates that cognitive task engagement might have differential effects on different response indices and that cortical modulation could be selective but not global.

The current results also contradict Galbraith and Kane (1993) who found no attentional modulation of brainstem FFRs, but did find attentional modulation of the cortical event-related potentials. This difference in results between the two studies may be due to methodological differences. In the present study, the authors used an active cognitive task that demanded mental calculations while recording FFRs during speech rather than a simple paradigm of directed auditory attention to low-frequency tonal stimuli, used by Galbraith and Kane.

In situations where the demands of the task differ, there may be more of a cognitive load, which could activate greater cortical responses and lead to measurable modulation of specific FFRs. The mechanisms underlying the observed increase in H2 and H3 amplitudes are not known, but the observations are consonant with an increasing literature suggesting that the FFR is not solely a brainstem response, but may reflect cortical activity and corticofugal mediation. A marked increase in the amplitudes of H2 and H3 during cognitive task engagement, combined with the large effect sizes found, indicate that attentional and cognitive processes can modulate aspects of auditory neural encoding. Thus, this study offers indirect support for a role for the cortex in scalp-recorded FFR and for a potential top-down, auditory modulation of speech processing.

5.3 Effect of Context Dependent Encoding on FFR

The present study also investigated whether there is a relationship between cognitive task engagement and context-dependent encoding of speech, as measured by the FFR. To get context-dependent encoding, the amplitude of the variable paradigm was subtracted from the one of the repetitive paradigm for the following parameters: F0, H2, H3, H4, and F1. It was

hypothesized that if engagement of the cognitive task modulated context-dependent encoding, the difference between the FFR amplitudes obtained from the repetitive and variable stimulus paradigms would differ between the task and no-task conditions. In particular, it was hypothesized that the engagement in cognitive tasks would modulate the extent of context-dependent encoding by affecting the interaction between the predictability of the stimuli and attentional/cognitive demand. The results, however, did not support this assumption. No consistent pattern of context-dependent encoding was found across the measured FFR components for the cognitive task or no-task condition.

The individual data of the indices (difference of the two paradigms) revealed that most participants did not show a difference between the repetitive and variable paradigms. Also, the amplitude differences were in either direction (positive or negative) among participants, indicating that there was no consistent direction of context-dependent enhancement, suggesting lack of evidence for context-dependent encoding effect.

The underlying idea of study on the influence of cognitive task engagement on context-dependent encoding was rooted in previous findings that stimulus regularity and top-down neural mechanisms influence auditory processing. Chandrasekaran et al. (2009) suggested that strengthened neural representation of speech stimuli in repeated situations could be due to corticofugal modulation of subcortical auditory processing. These results have been interpreted as the dynamic tuning of neural encoding to the statistical regularities in the acoustic environment.

A significant interaction between stimulus paradigm and cognitive task engagement would be predicted if cognitive task engagement had resulted in changes to context-dependent encoding. This kind of interaction would suggest that the effects of the difference between the repetitive and variable stimuli paradigms was dependent on the presence or absence of the

cognitive task. However, no significant interaction effect was observed. This indicates that the effect of cognitive task engagement on the FFR was not dependent on stimulus regularity and that the neural systems involved in context-dependent encoding were not significantly affected by the cognitive task used in the present study. Thus, the present results indicate that there is no evidence here that cognitive task engagement affected context-dependent encoding of speech as measured by the FFR.

A modulation of context-dependent encoding was not observed in the present study. There was no interaction effect for stimulus paradigm and cognitive task engagement, indicating that cognitive task engagement did not systematically change the neural effects produced by stimulus regularity. Thus, these results do not suggest that cognitive task engagement influenced the context-dependent representation of speech in the FFR.

5.4 Implications to Cortical Contributions to FFR

The present study aimed to investigate the role of the cortex in the FFR generation by investigating the interaction between stimulus paradigm and cognitive task engagement in generating speech-evoked neural responses. Traditionally, the FFR has been thought to represent a subcortical response that reflects phase-locked neural activity in the auditory nerve and brainstem nuclei, such as the inferior colliculus (Greenberg et al., 1981; Marsh et al., 1974; Smith et al., 1975). Evidence more recently however has indicated that the scalp-recorded FFR (Coffey et al., 2016; Coffey et al., 2017; Gnanateja et al., 2021) might also involve the activity of cortical auditory regions.

The results from the present study failed to reveal a strong context-dependent encoding effect, nor was a significant difference found between the stimulus paradigms. The present results do not support the idea that only stimulus regularity, in the present experimental context, creates neural encoding via corticofugal mechanisms. But both H2 and H3 showed significant

increases when engaged in cognitive task, and both showed large effect size. The selective enhancement of these harmonic components indicates that some components of speech encoding may be sensitive to cognitive effects in the FFR.

These results provide evidence for cortical contributions to the FFR, in agreement with the findings of Coffey et al., who demonstrated using MEG that auditory cortical activity contributes to the generation of scalp-recorded FFRs. Likewise, Hartmann and Weisz (2019) found that attentional modulation of the FFR was limited to the right auditory cortex, and Gnanateja et al. (2021) found that volume conduction is responsible for the scalp-recorded responses of cortical FFRs. These studies indicate that the FFR is composed of integrated neural activity from both cortical and subcortical auditory structures.

The present study's methodology did not allow direct identification of the locations of neural generators associated with the increased responses seen at H2 and H3, but the increase in amplitude at H2 and H3 during cognitive task engagement compared to its counterpart could be interpreted as the effect of top-down cortical processes on neural encoding of the auditory stimulus. This modulation might happen via corticofugal pathways linking the cortex to subcortical nuclei and which affect the representation of acoustically salient speech cues (Chandrasekaran & Kraus, 2010; Maruthy et al., 2017) results of the present study then indirectly suggest that the FFR is influenced by the cortical activity, if not partly generated by cortical sources.

In summary, the results indicate that the cognitive task engagement has a greater impact on the FFR than stimulus regularity. The results suggest that the FFR is not a purely subcortical phenomenon, and that scalp-recorded FFR may be affected by higher-order cortical activity, but are not definitive enough to prove the existence of cortical generators of the FFR.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The Frequency Following Responses (FFRs) are sustained auditory evoked potentials that reflects neural phase-locking to periodic aspects of the speech stimulus and has been widely used as an index of subcortical auditory encoding. While the FFR is primarily generated at subcortical levels such as inferior colliculus, converging evidence suggests that the cortical regions also contribute to the scalp recorded response, particularly under the conditions that engage attention and top-down processing. Context dependent encoding of the FFR, as demonstrated through comparisons between repetitive and variable stimulus paradigms, has been attributed to corticofugal modulation of subcortical auditory processing. The aim of the present study was to explore the effect of attention on the context dependent encoding of the FFR, by employing cognitive task engagement, thereby inferring on the influence of cortical areas and corticofugal pathways on the generators of FFR.

Twenty normal hearing adults in the age range of 18 to 25 years participated in the study. FFRs were recorded using a single channel vertical montage in response to a synthetically generated /da/ syllable of 100 ms duration, borrowed from Maruthy et al. (2017). Recordings were obtained in four experimental conditions derived from two stimulus paradigms (repetitive & variable), each presented with and without concurrent cognitive task engagement. In the repetitive paradigm, only the /da/ stimulus was presented. Whereas in the variable paradigm, /da/ was presented alongside contextual syllables /bi/, /bu/, and /gi/, all four at equal probability. The cognitive task consisted of mentally solving simple arithmetic calculations that were presented on a screen and indicating correct answers by raising the index finger.

FFRs were analysed using custom written program in Matlab R2023b platform to derive the spectral magnitudes at the first four harmonics (H1, H2, H3 & H4) and the first formant (F1). Statistical analysis was performed to compare FFR amplitudes in repetitive and variable stimulus paradigms, with and without the cognitive task. Additionally, an index of context-dependent encoding was computed by calculating the difference in spectral amplitudes obtained from the repetitive and variable stimulus paradigms, for comparing between task and no task conditions. Repeated measures ANOVA was used to examine the effect of stimulus paradigm and engagement in the cognitive task on the amplitudes of F0, H2, H3, H4, and F1.

The results indicated that there was a significant main effect of cognitive task engagement on H2 and H3 amplitudes, with both harmonics having higher amplitudes in the with-task condition than in the without-task condition. No significant main effect of cognitive task engagement was found for F0, H4, or F1 amplitudes. There was no main effect of stimulus paradigm on any of the spectral components. No significant main effects were found for F0 amplitude but there was a significant interaction between stimulus paradigm and cognitive task engagement. The derived index of context dependent encoding did not show a consistent pattern of presence of context-dependent encoding.

Overall, the findings indicate that cognitive engagement influences specific features of the speech-evoked FFR, whereas the effect of stimulus context appears to be limited. Specifically, significant increases in the amplitudes of H2 and H3 were observed during the cognitive task condition compared to the no-task condition. In contrast, the repetitive and variable stimulus paradigms did not produce consistent differences in neural encoding across participants, suggesting a lack of robust context-dependent encoding. Furthermore, the observed enhancements in H2 and H3 amplitudes were not accompanied by corresponding

changes in other FFR components. Taken together, these findings provide indirect evidence for the involvement of cortical and corticofugal mechanisms in shaping scalp-recorded FFRs.

Future studies employing more demanding cognitive tasks, high-density EEG recordings to facilitate source localization, research-grade electrophysiological recording systems, and direct measures of cortical activity are warranted to further elucidate the contribution of cortical processes to auditory neural encoding and the generation of speech-evoked FFRs.

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