EFFECT OF STIMULUS POLARITY ON CONTEXT DEPENDENT BRAINSTEM ENCODING OF SPEECH

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Register No.: 17AUD033

A Dissertation Submitted in Part Fulfillment of Degree of Master of Science

(Audiology)

University of Mysore

Mysuru

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May, 2019

CERTIFICATE

This is to certify that this dissertation entitled **'Effect of polarity on context dependent brainstem encoding of speech'** is a bonafide work submitted in part fulfillment for degree of Master of Science (Audiology) of the student Registration Number: 17AUD033. 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.

Mysuru

May, 2019

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CERTIFICATE

This is to certify that this dissertation entitled **'Effect of polarity on context dependent brainstem encoding of speech'** has been prepared under my supervision and guidance. It is also 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 **'Effect of polarity on context dependent brainstem encoding of speech'** is the result of my own study under the guidance of Dr. Sandeep M., Associate Professor in Audiology, Department 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, **Registration No. 17AUD033**

May, 2019

DEDICATED TO MY PAPA

Acknowledgement

I thank my guide Dr. Sandeep M. whole heartedly. Thank you so much sir for being so patient with me. It would have been very difficult to finish my dissertation without you. I thank you immensely for not giving up on me.

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

I thank Dr. Sujeet Sinha, HOD, All India Institute of Speech and Hearing, Mysore for permitting me to use the department.

Special thanks to Indira ma'am, Jim Sir, Sharath Sir, Shubha ma'am, Priyadarshini ma'am for their valuable support and inputs.

I thanks Reesha ma'am, one of the important person who make possible to complete the data collection on time.

Thanks Sneha to be my 2nd m sc time keeper. You always pushed me to do the work with more concentration.

Thanks Deeksha (motu) to being always my side. You always remind me, what is important to me, and what is my goal.

I thank all the 4oHz for all their love and support.

Thank you all my AYJ classmates, juniors, seniors and staff for making the base of speech and hearing.

`A very special thanks to bhai, mummy and didi for all your love and care since childhood.

Last but not least my Late father. You mean everything to me. Thank you for showering all your blessings.

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Chapter 1

INTRODUCTION

In our daily life, we all encounter auditory scene that usually comprises of many different simultaneous sources and challenges the verbal communication. If two individuals are communicating in a noisy place such as cafe or restaurant, for the effective communication, the listener has to extract and rely on the necessary cues from the background noise and this extraction of cues is particularly challenging if there is overlapping acoustic properties of competing with the target signal. Yet, in most instances, communication is spared even in such adverse conditions remarkably due to highly adaptive characteristics of auditory system that constantly attune its actions based on the contextual demand. Earlier studies have shown that supported that the auditory system has the efficiency to extract harmony from an on-going signal and it is the fundamental for unhindered perception of speech in background noise (Chandrasekaran, Hornickel, Skoe, Nicol & Kraus, 2009; Winkler, Denham &Nelken, 2009).

Recordable brainstem response to speech (speech ABR) has offered a unique way of understanding and analyzing the representation of the speech components at the brainstem level. The onset and a sustained frequency following responses (FFR) are two unassociated components of brainstem responses. Each converging different information about the brainstem signal property. The scalp recorded onset responses and the FFRs reflect the activity at numerous sources throughout the brainstem such as cochlear nucleus, Lateral Lemniscus and Inferior Colliculus. FFRs closely mimic the incoming signal and reflect neuronal phase-locking to fundamental frequency, as well as its harmonics (Chandrasekaran & Kraus, 2010). The extent of mimicking in

FFR is shown in study done by Galbraith et al., 1997, in which FFRs recorded for them were played back, subjects could identify the words with greater-than-chance accuracy. FFR can be used as an index for long-term and training-related neural plasticity as demonstrated in various studies (Krishnan &Gandour, 2009; Krishnan et al., 2005).

Comparison of FFRs elicited with two different stimulus contexts, a predictable context versus a highly variable context has shown that the representation of brainstem response is context-dependent (Chandrasekaran et al., 2009) and the repetition induces improved neural representation of cues which are relevant for perceiving pitch of voice and Pitch perception being an important cue for segregating sound sources in noisy environments, it was hypothesized that the repetition-induced plasticity in representation of voice pitch would be strongly associated with behavioural performance on speech-in-noise tests. Their result suggests that the ability to fine-tune brainstem encoding of repeating elements in the auditory environment is essential for speech perception in noise.

The existing evidences suggest malleability in the brainstem representation of speech (Kraus & Nicol, 2005, Banai Nicol, Zecker & Kraus, 2005). Both long-term and short-term auditory experiences have been shown to enhance the brainstem responses to complex behaviourally relevant sounds. The neurobiological mechanisms that contribute to this plasticity is unknown. Presently, two hypotheses on the nature of experience dependent brainstem plasticity are being debated (Krishnan & Gandour, 2009). One is the corticofugal model (Suga, Xiao, Ma & Ji, Suga, 2011) and the other is the local reorganization model (Krishnan & Gandour, 2009).

1.1 Justification for the Study

Chandrasekaran, Hornickel, Skoe, Nicol and Kraus (2009) elicited brainstem response to speech syllable /da/ in two conditions; variable and repetitive conditions. The results showed that there was a significant difference between the brainstem responses elicited in two conditions. The response elicited in the repeated condition was enhanced in the lower harmonics and first formant range relative to the variable context condition. Similar results have been reported by Tonse and Maruthy (2012). In their study, to obtain information on the extent to which plasticity is operational online, brainstem response to speech syllable /da/ was elicited in four conditions, which included one repetitive condition and three stimulus context conditions. Results showed that the latencies of onset and sustained responses were prolonged in the stimulus context conditions when compared to repetitive condition.

Many other literature evidences support the above mentioned findings (Chandrasekaran et al., 2009; Gnanateja, Ranjan, Firdose, Sinha & Maruthy, 2013; Maruthy et al., 2017; Parbery-Clark, Strait & Kraus, 2011; Skoe & Kraus, 2010; Strait et al., 2011). But Shruthi (2018) showed a different behaviour of the context dependant brainstem encoding wherein larger amplitude of formant in the variable condition was found than repeated condition, in quiet as well as in presence of noise.

Studies which show the trend of the greater amplitude in the repetitive condition (Chandrasekaran et al., 2009; Gnanateja, Ranjan, Firdose, Sinha & Maruthy, 2013; Maruthy et al., 2017; Parbery-Clark, Strait & Kraus, 2011; Skoe & Kraus, 2010; Strait et al., 2011) had been carried out with the alternative polarity whereas Shruthi (2018) used single polarity i.e. rarefaction. Thus, there is a need to investigate the effect of polarity on context dependent encoding of FFRs. Alternating polarity and the single polarity are known to generate sustained responses of different nature. Therefore, it is possible that the nature of context dependent encoding is different for responses elicited in the two polarities. The comparison of the context dependent encoding elicited in the two polarities thereby is likely to shed more light on the mechanisms of context dependent encoding. Hence the present study was taken up.

1.2 Aim and Objectives of the Study

The aim of the study was to determine the effect of the stimulus polarity on the context dependent brainstem encoding of the speech. The specific objectives were to compare: The

1) Context dependent encoding of FFR recorded in rarefaction and alternative polarity

2) Context dependent encoding recorded for rarefaction and alternative polarity stimuli in terms of their relationship with speech perception in noise.

Chapter 2

REVIEW OF LITERATURE

Histroically, the brainstem was considered as a passive structure by researchers, and it was common belief that only the cortical structures actively participate in speech perception and higher-level speech processing.

However, studies on animal models have brought to light evidence to show that lower perceptual structures like the auditory brainstem are crucial for processing auditory signals in a noisy environment (Luo et al., 2008). Also, studies on human subjects has revealed that the auditory brainstem faithfully preserves the complex harmonic characteristics of speech (Johnson, Nicol, & Kraus, 2005). This is observed during non-invasive measurement of responses to speech from the lower levels of the central nervous system such as the auditory brainstem (Johnson et al., 2008; Hornickel et al., 2009), called the Frequency following response (FFR) or complex ABR (cABR) or speech ABR.

The FFR closely mimics the incoming signal. So much so that when FFR waveforms recorded for words is played back, we can understand the words with greater than chance accuracy (Galbraith et al., 1995). FFR has been shown to be sensitive to training and experience, as seen by their sensitivity to language (Krishnan et al., 2009; Xu et al., 2006) musical experience (Bidelman et al., 2014; Lee et al., 2009), short, and long term auditory adaptation and training (Russo et al., 2005; Song et al., 2008). FFR has also been shown to encode the missing fundamental frequency (Gnanateja, Ranjan, Firdose, Sinha, & Maruthy, 2013), which provides evidence for the brainstem's participation in speech perception in difficult to listen situations, by encoding the envelop of the stimulus.

It may be stated that the FFR/cABR is used to report training and experience related changes and also to examine the fidelity of stimulus encoding at the level of brainstem in the presence of noise. Hence, stimuli used for recording the responses should provide fine-grained measures of phonetic information processing that clinical population has particular difficulty perceiving (Russo et al., 2014). The most commonly used stimulus to record the cABR is the syllable /da/. This stimulus consists of an onset burst frication for 10ms, followed by F1 and F2 transitions for 30ms. The stimulus does not have steady state portion of the vowel. Nevertheless, it is perceived as a syllable by the listeners. This stimulus, though contains most important acoustic-phonetic information of the syllable, is short enough in duration to minimize test time.

2.1 The cABR Responses

The cABR responses may be broadly divided into the transient and sustained portions. The transient portion of the responses depict the encoding for rapid onsets and rapid frequency shifts, like consonant onsets and fast frequency sweeps respectively. The sustained portion of the cABR is called the FFR in general. This portion usually codes for the vowel portion of the stimulus, and can be elicited by any periodic stimulus up to around 1000Hz (Sohmer et al., 1977; Krishnan et al., 2005). Multiple brainstem sites have been reported to contribute to the generation of the cABR or the FFR. However, the primary generators, as reported in literature are the fluctuation of the endolymph at the apex of the cochlear hair cells and the phase locking of excitatory post synaptic potentials of neurons in the inferior colliculus (Bledsoe & Moushegain, 1980).

2.2 Applications of Speech-evoked Brainstem Response

Neurodevelopmental disorders characterized by impaired communication and literacy skills such as dyslexia or Autism spectrum disorder have been associated with the abnormal subcortical representation of speech. Disruption in the FFR is found in children with deficit in phonological awareness, reading and abnormal timing resolution (Abrams et al., 2006; Banai et al., 2009). Children with reading or language disorders have significantly slower neural response timing, the weak neural encoding of formant related stimulus harmonics and less robust tracking of frequency contours than typically developing children (Banai et al., 2005; Basu et al., 2010; Billiet & Bellis., 2010).

Approximately 40% of the children with dyslexia show abnormal brainstem encoding of speech (Banai, 2005). Abnormal finding in brainstem encoding suggests that this may serve as a reliable marker of a subgroup of an individual with dyslexia/learning disability (Banai, 2005). Children with dyslexia are characterized by the delayed and harmonically impoverished response from the auditory information from the auditory brainstem (Banai et al., 2009; Hornickel et al., 2012, 2011), reduced subcortical representation of difference in stimulus (Banai et al., 2005; Hornickel et al., 2009), and poor context dependent encoding (Chandrasekaran et al., 2009) .

Russo et al. (2009) observed that FFR recordings from the Autism spectrum disorder (ASD) children exhibited a deficit in timing and frequency encoding of a speech sound at the brainstem level. ASD individual also showed a subcortical neural response which was more vulnerable to background noise in comparison to typically developing children.

2.3 Modulation in the Brainstem Physiology Secondary to Long Term Exposure to Language and Music

FFRs demonstrate changes in response to training and exposure to language and music (Krishnan et al., 2004). This means that they could serve as an index of long term, and training related plasticity. FFRs are influenced by long term language learning, but these potentials recorded from listeners vary depending on how F0 cues are used to signal pitch contrast in the their native language (Krishnan et al., 2004). Native speakers of tonal languages, like Mandarin exhibit robust representation of voice pitch compared to speakers of non-tonal languages (Krishnan & Gandour, 2009; Krishnan et al., 2005). In their cross-language study, Krishnan, Xu, Gandour, and Cariani (2005) showed that native speakers of Mandarin had significantly better representation of linguistic pitch contours reflected by FFRs, as compared to native speakers of American English. This better representation of pitch contours was seen only for naturally occurring Mandarin pitch contours and not for their linear approximates.

Krishnan, Swaminathan, and Gandour (2008) conducted a cross-language study wherein they simulated Mandarin tones using iterative ripple noise (IRN). These stimuli, though non-speech in nature, elicited preserved complex pitch at the level of brainstem in native speakers of Mandarin. This was not seen in English speakers. The findings indicate that brainstem plasticity is not specific to speech; rather it is specific to dimensions that appear in natural speech.

2.4 Mechanisms Underlying Experience-Dependent Plasticity

Existing evidence suggests that brainstem representation of speech is malleable, and that the changes occur in response to short term as well as long term auditory experiences (Kraus & Nicol, 2005; Banai Nicol, Zecker & Kraus, 2005). In addition, the initial evidence from study by Chandrasekaran, Hornickel, Skoe, Nicol, and Kraus (2009) showed that the human auditory brainstem is sensitive to ongoing stimulus context also. Feedback related to top-down control provided by the massive efferent connection from the cortex to subcortical structures is attributed to be the reason for this observation (Winer, 2005).

It is hypothesized that corticofugal pathways help to selectively amplify the relevant information presented in the presence of noise, and inhibit the coding of irrelevant information at the very early stages of auditory processing. Such a feedback mechanism will be helpful in speech perception in the presence of noise (Luo et al., 2008). Hence, the auditory cortex, via the corticofugal pathways is able to improve signal quality by modulating the response properties of brainstem neurons (Gao & Suga, 1998, 2000).

However, the mechanisms behind this experience-related plasticity as well as the involvement of the cortico-fugal pathways is presently unknown. However, two hypotheses on the nature of experience-dependent brainstem plasticity are being debated (Krishnan & Gandour, 2009). One is the corticofugal model (Suga, 2011) and the other is the local reorganization model (Krishnan & Gandour, 2009).

The corticofugal model proposes that top-down feedback via the corticofugal efferent network modifies brainstem function (Suga, 2008; Suga et al., 2002), whereas the local reorganization model states that the brainstem reorganization happens over a longer timescale (Krishnan & Gandour, 2009). The corticofugal model predicts that as a result of top-down feedback, there are moment-to-moment changes in brain function. The local reorganization model, on the other hand, states that the brainstem re-organization happens to promote the encoding of frequently encountered sounds. Both the models refer to top-down feedback for the mentioned modulations during learning period. After the learning period the feedback mechanisms are not required. Hence, both the models propose that top-down feedback mechanisms modulate the brainstem responses, albeit at vastly different time scales.

2.5 Context-dependent Encoding of Speech

Context dependent encoding of speech is an indicator of influence of an active feedback mechanism that functions online. Considering that speech presented in different contexts gets encoded at the level of brainstem in the presence of such a mechanism, it would be evidence for brainstem plasticity that happens as a continuous process.

Chandrasekaran, Hornickel, Skoe, Nicol and Kraus (2009), Parbey-Clark et al. (2011) and Strait et al. (2011) recorded FFRs for syllable /da/ in two different contexts; variable /low-predictable context and repetitive/high-predictable context. The contextual syllables used by Chandrasekaran et al. (2009) and strait et al. (2011) were different in their pitch contours, voice-onset times, place of articulation and vowel lengths. They observed that the brainstem responses elicited for /da/ in the repetitive/high-predictable context had greater spectral amplitude compared to those recorded in the variable/low-predictable context. This was observed in children without developmental dyslexia and not in children with developmental dyslexia (Chandrasekaran, Hornickel, Skoe, Nicol & Kraus, 2009). They also observed a correlation between extent of context dependent encoding and bevioural speech in noise perception.

To obtain information about the degree to which brainstem plasticity is operational online, Tonse and Maruthy (2012) recorded cABRs to speech. Brainstem responses to the syllable /da/ was elicited in one repetitive and three different stimulus context conditions. The latencies of onset as well as sustained portions of the responses obtained for /da/ in the stimulus context conditions were prolonged. The brainstem generators of these responses, ie., the CN, IC and the LL fall within the feedback loop of the corticofugal pathway. Hence, the authors theorize that the corticofugal pathway has the ability to identify spectral differences between the target stimulus and contextual stimulus. This in turn is hypothesized to influence the brainstem responses. The results of the study suggest the possibility of online plasticity at the level of brainstem, mediated and regulated by the corticofugal network. On similar lines, Gnanateja et al. (2013) found that spectral structure too is a parameter that cues context-dependent encoding of speech in the brainstem. Skoe and Kraus (2010) reported enhancement in the brainstem representation of locally repeating note in a five-tone melody played repeatedly over a duration of 1.5 hours.

Better encoding of fundamental frequency for stimuli presented repetitively indicates that the encoding of sounds in the brainstem is continuously influenced by the on-going sound statistics (Skoe & Kraus, 2010). This points to an online active feedback system, which alters the encoding of sounds based on the incoming sound statistics. The corticofugal system is one such network, which, based on cortical feedback, regulates and modifies the brainstem encoding of the incoming sound (Zhang & Suga, 1997).

Clark, Strait and Kraus (2011) showed that musicians have enhanced subcortical sensitivity to speech regularities helpful in improved speech perception in the presence of noise. They examined context dependent encoding of speech in syllable in musicians and non-musicians. They observed robust neural encoding of fundamental frequency of the speech stimulus in the predictable/repetitive condition than in the variable condition in musicians, as compared to non-musicians. They also observed that the neural encoding precision correlated with the musicians' musical practice as well as their speech perception in noise abilities.

In her study to explore the effect of noise on context dependent encoding of speech, Shruthi (2018) recorded FFRs using a /da/ stimulus of 100ms duration in a repetitive paradigm as well as in contextual paradigm with /bu/, /gi/ & /bi/ syllables, both in the presence of noise at +10 dB SNR as well as in quiet. The testing was done on adult participants with normal hearing sensitivity. Findings of the study reveal that encoding of the target stimulus was better in variable paradigm in the quiet as well as noise conditions.

2.6 Effect of Polarity on the Speech ABR

The FFR recordings shows response that the envelop and spectrum of the stimulus which are referred as the envelop FFR and spectral FFR respectively (Aiken & Picton, 2008). The stimulus polarity referred to the initial direction of deflection on the diaphragm of transducer. The three type of the polarity used in the AEP measurements are (1) Rarefaction (initial outward movement) (2) Condensation (initial inward movement), and (3) alternating (stimulus presented alternatively in two polarities).

The long duration of the FFR stimulus chance to stimulus related artefact and cochlear microphonics (CM) interfere in processing window of FFR recordings. To avoid such processing complications to two different method suggested in the literature (1) recording the FFR in alternating polarity (Chandrasekaran., 2007), and (2) subtractive method recording the FFR in single polarities and for equal number of sweeps then subtract two recording to eliminate the stimulus artefact and CM (Greenberg et al; 1987). Majority of the FFR based studies done with the alternating polarity due to less time consuming and easy to obtain the response as compare to subtractive method. Krishnan (2007) proposed that recording in the alternating polarity of stimulus locked to the envelop of the stimulus and single polarity locked to the spectral feature of the stimulus. The use of the alternating polarity will eliminate the CM from the response but only gives the response to the envelop of the stimulus. Chimento and Schreineer (1990) point out that the use of the alternating polarity severely distort the spectral component of the FFR.

On the other side subtractive approach is analogous to the compound histogram technique use in the neurophysiological studies (Anderson et al., 1971). Subtractive method done by the taking the equal number of responses with the rarefaction and condensation polarity and average them together. This approach help in the eliminating the stimulus related artefact but the stimulus related artefact still present.

Subtractive method as well as alternating polarity method both are equally efficient in the eliminating the distortion generating during the neural transduction. Krishnan (2002) suggested that the alternating polarity can be used to record the response to envelop and subtractive method can be used to record the spectral feature of the stimulus.

Various studies point out the effect of stimulus one transient evoked ABR. So it can be expected that the polarity of the stimulus may have significant effect on the speech ABR also. In the recent past various researcher recorded the speech ABR in different polarities (Aiken & Picton, 2008; Russo et al., 2004; Song et al., 2008). Kumar et al. (2013) studied the effect polarity on speech ABR. They reported that single polarity gives significantly higher amplitude than the alternating polarity, and rarefaction polarity and condensation polarity didn't shown any statistical difference (Kumar, Bhat, D'Costa, Srivastava & Kalaiah, 2014).

In summary, brainstem responses to complex stimuli like speech provide an opportunity for researchers to understand finer aspects of brainstem encoding of different components of speech. Provided that evidence shows that scalp recorded FFRs are generated from brainstem structures, they provide a means to better understand mechanisms of speech encoding at the brainstem structures. Research has also found evidence for cortico-fugal modulations of these responses in context dependent encoding of these stimuli. Context dependent encoding of speech also has the potential to indicate a person's ability to perceive speech in the presence of noise.

Chapter 3

METHODS

The primary aim of the study was to investigate the effects of the stimulus polarity on the context-dependent encoding of the brainstem responses and to determine the relationship between speech perception in noise and context-dependent brainstem encoding elicited in the two polarities. Grossly, the method involved recording context-dependent brainstem encoding in different polarities and speech perception in noise in a group of adults. The method used conformed to the institutional ethical guidelines stipulated for bio-behavioral research in humans (Venkatesan, 2009). The specific details of the method used are given in the subsequent sections.

3.1 Participants

Participants included twenty-two young adults in the age range of 18 to 26 years. They exhibited normal auditory and speech-language abilities. They had their hearing sensitivity within 15dBHL at octave frequencies between 250Hz and 8000Hz, normal results in tympanometry and reflexometry, word recognition score of more than 90% in each ear, normal findings in otoacoustic emissions and normal auditory brainstem responses. They did not report of any complaints that are suggestive of present or past otological or neurological disorders. The participants did not report of difficulty in understanding speech in noisy conditions.

All the participants were native speakers of either Kannada or Telugu. The native speakers of these two languages were selected considering that they share the same phonetic inventory. They were pursuing bachelors or Master’s Degree at the All

India Institute of Speech and Hearing, Mysuru and were not familiar with either the purpose or hypothesis of the study. In order to ensure homogeneity among the participants, musicians were excluded from the study. An informed consent was obtained from all the participants prior to their inclusion in the study and all the participants were tested only in their right ear.

3.2 Test Stimuli

Four different stimuli were utilized to record context-dependent brainstem encoding. Of these four, one was a target stimulus and the other three were used as contextual stimuli. A synthetically generated syllable /da/ was the target stimulus. Only the response recorded for syllable /da/ was of importance in the present study. The other three syllables that served as contextual stimuli were, /bu/, /bi/ and /gi/. The contextual stimuli differed from /da/ syllable in terms of burst of the stop, second formant transition and the vowel.

The syllable /da/ was of 100ms. Longer duration was preferred because the spectral information was better represented and better FFR were being recorded than that with shorter duration /da/ (40ms). The syllables /da/, /bu/, /bi/ and /gi/ were borrowed from Shruthi (2018). These were synthetic stimuli generated based on linear predictive coding parameters. The details of the stimulus generation and its parameters can be found in Shruthi (2018). The waveforms and spectrograms of the four stimuli used in the present study are shown in Figure 3.1. The spectral characteristics are shown in Table 3.1.

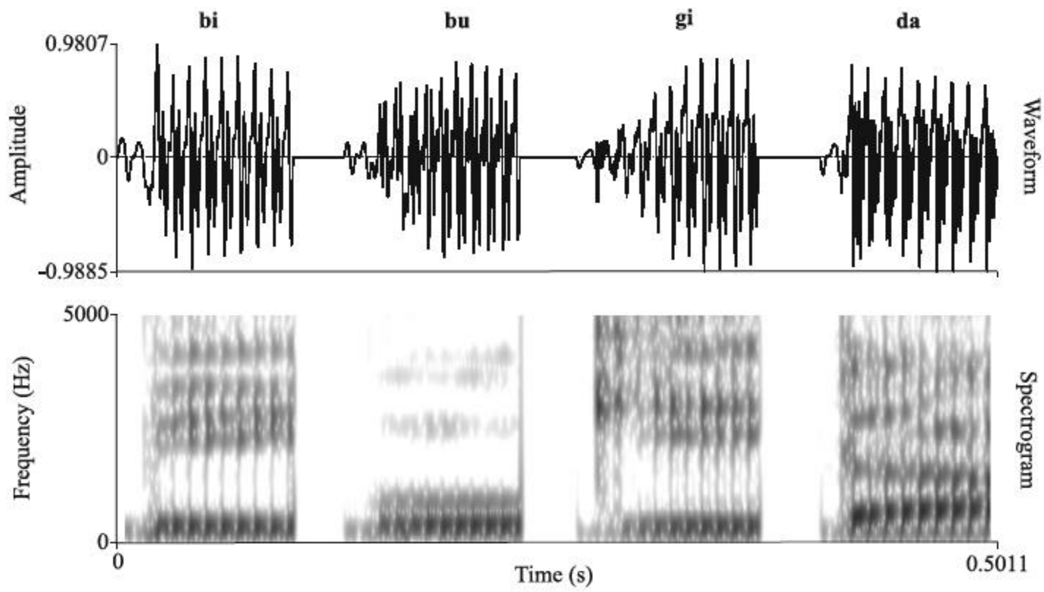

Figure 3.1: The waveforms and Spectrograms of syllables /bi/, /bu/, /gi/ and /da/, generated and used in the present study.

Table 3.1: Spectral characteristics of syllables, /bi/, /bu/, /gi/ & /da/ 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 the tests were carried out in an electrically and acoustically shielded room. The ambient noise in the room was well within the permissible limits prescribed by ANSI/ASA S3.1-1999 (R2013).

3.4 Test Procedure

The test procedures in the study are reported under two broad headings; candidacy assessment and the experimental test procedure.

3.4.1 Candidacy assessment

The purpose of the candidacy assessment was to ensure that the participants fulfilled all the selection criteria mentioned in section 3.1. The procedures included structured interview, puretone audiometry, speech audiometry, immittance evaluation, otoacoustic emissions and auditory brainstem responses. The ear-specific ***puretone thresholds*** were tracked at octave frequencies between 250Hz and 8kHz using Inventis Piano audiometer with TDH-39 headphones. The modified Hughson and Westlake method was used to track the thresholds in the air conduction and bone conduction modalities.

Speech audiometry included estimating speech recognition threshold and speech identification scores. Speech recognition threshold was estimated using pair-words using the standardized procedure (Wilson et.al., 1973; ASHA.,1988) and the speech identification score was assessed at 40dBSL (Ref: speech recognition threshold) using the phonemically balanced word test in the respective language. The same audiometer used for puretone audiometer was used for speech audiometry.

Immittance of the middle ear was assessed using GSI Tympstar middle ear anlayzer. 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 & ear canal volume) were noted down to interpret the middle ear status. Subsequently, the ipsilateral and contralateral reflex thresholds were recorded for puretones of 500Hz, 1 kHz, 2 kHz and 4 kHz.

Transient evoked otoacoustic emissions (TEOAEs) were recorded for clicks presented at around 80dBpkSPL, presented in nonlinear stimulus paradigm. ILO-292 Echoport plus (version 6) was used to record and analyse TEOAEs. Amplitude of TEOAEs were noted down at octave and mid-octave frequencies between 1kHz and 6kHz. All the measures of the candidacy assessment were obtained from each ear of the participants.

3.4.2 Experimental test procedure

The participants who fulfilled all the necessary qualifications mentioned in section 3.1 were subjected to the actual experimental procedure of the study. This included measurement of speech perception in noise in terms of SNR-50 and context dependent brainstem encoding

Speech perception in noise (SNR-50) estimated the speech to noise ratio at which 50% of the monosyllables could be identified (SNR-50). SNR module of the Smriti-shravan software developed by Kumar and Maruthy (2016) was used for this purpose. A laptop computer with a Sennheisser HDA-200 headset, the output of which was calibrated, was used to deliver the test stimuli. The module used 19 bisyllables (syllables shown in figure 3.2) mixed with broadband noise at varying SNRs. One-down one-up procedure was used for finding the SNR-50. The test would begin with SNR of 20dB with subsequent reduction in SNR in 2dB steps for every correct response and increase in 2dB steps for every incorrect response.

Participants were instructed to listen the words carefully, recognise or guess the bisyllable heard and indicate the response by clicking on the respective bisyllable among the 19 bisyllables displayed on the computer screen. Initial 10 reversals were given for the practice and familiarity of the test and the average of additional 4 reversals were taken as the SNR-50.

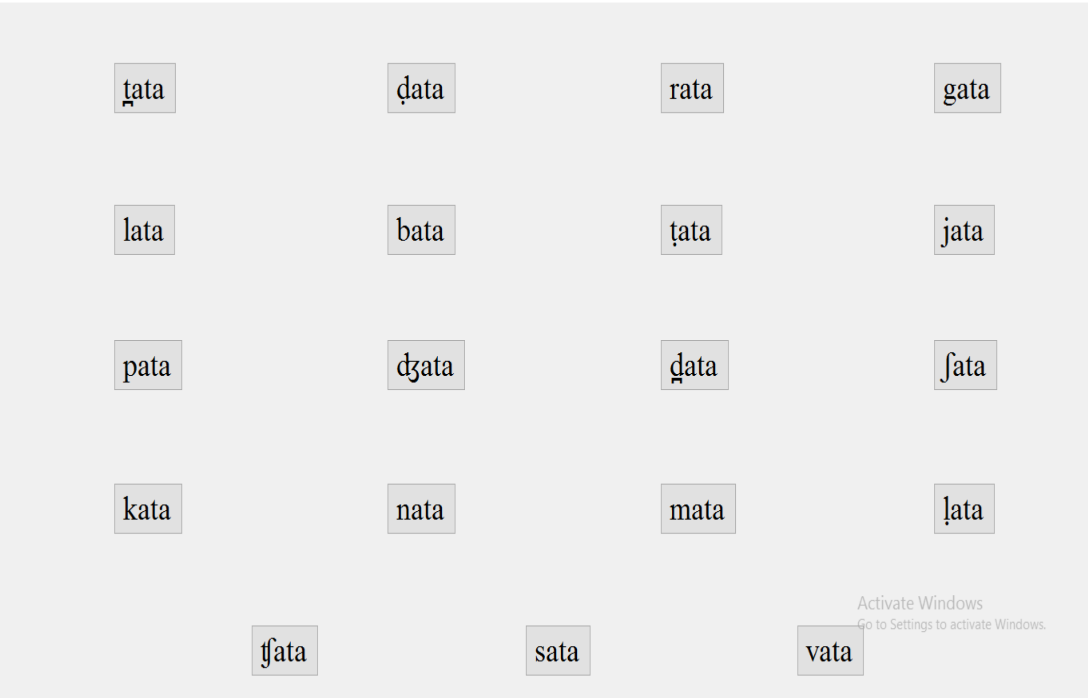

Figure 3.2: Nineteen bisyllables displayed on the computer screen during SNR-50 estimation using Smriti-Shravan module.

Context dependent encoding of the brainstem responses was recorded for stimulus being presented in rarefaction and alternating polarity. The participants were seated in a sound treated and electrically shielded room. Intelligent hearing systems hardware with Smart EP software (Version 2.72) was used to record the frequency following responses (FFRs). A single channel recording with electrodes placed in vertical ipsilateral montage (right mastoid-negative, Fpz-ground & Cz-positive) was used for recording the response. The electrode sites were prepared with skin preparation gel, following which gold plated electrodes were placed with conducting gel and adhesive tape. The absolute and the relative electrode impedance were maintained below 5kOhm and below 2kOhms respectively throughout the recording session. The participants were instructed to relax and minimize the extraneous movements of the head and neck region of the body, during the recording.

The specific stimulus and acquisition parameters used to record the brainstem responses are given in Table 3.2. The responses to synthetic /da/ were generated in two paradigms (repetitive and variable), each with stimulus being in either rarefaction or alternating polarities (2*2 stimulus conditions). In each condition, responses were recorded twice to ensure replicability of the waveforms.

In the condition 1, the FFRs were recorded by presenting the stimulus in a single polarity (rarefaction) in repetitive paradigm. Only the stimulus /da/ was presented in the rarefaction polarity and the responses were averaged for 1000 sweeps. This was followed by *condition 2* in which FFRs were recorded again in repetitive paradigm but this time the stimulus was presented in alternating polarity. Condition 3 and 4 were variable stimulus paradigms, with stimulus being in single polarity (rarefaction) in condition 3 and alternating polarity in condition 4. To present the stimulus in variable paradigm, stimulus paradigm of MMN/P300 protocol available in the Smart EP software was used. In this stimulus protocol, /bu/ was presented as the frequent stimuli with 50% probability while /da/, /bi/ and /gi/ were presented as the infrequent stimuli with 30%, 10% and 10% probability respectively. In this case again, FFRs were recorded for 1000 presentations of the /da/.

Table 3.2: represents the different paradigms in which FFR were recorded

Stimulus Parameters	
Stimuli	Repetitive paradigm: /da/ only Variable paradigm: /da/, /bi/, /bu/, /gi/
Ear	Right
Duration of stimulus	100 ms
Intensity	70 dBnHL
Repetition rate	7.1/s
Polarity	Rarefaction, condensation and alternating Polarity
Number of sweeps	1000
Acquisition Parameters	
Analysis time	128 ms
Electrode montage	Vertical
Amplification	100000
Artifact rejection	25 µV
Filter setting	30-3000 Hz

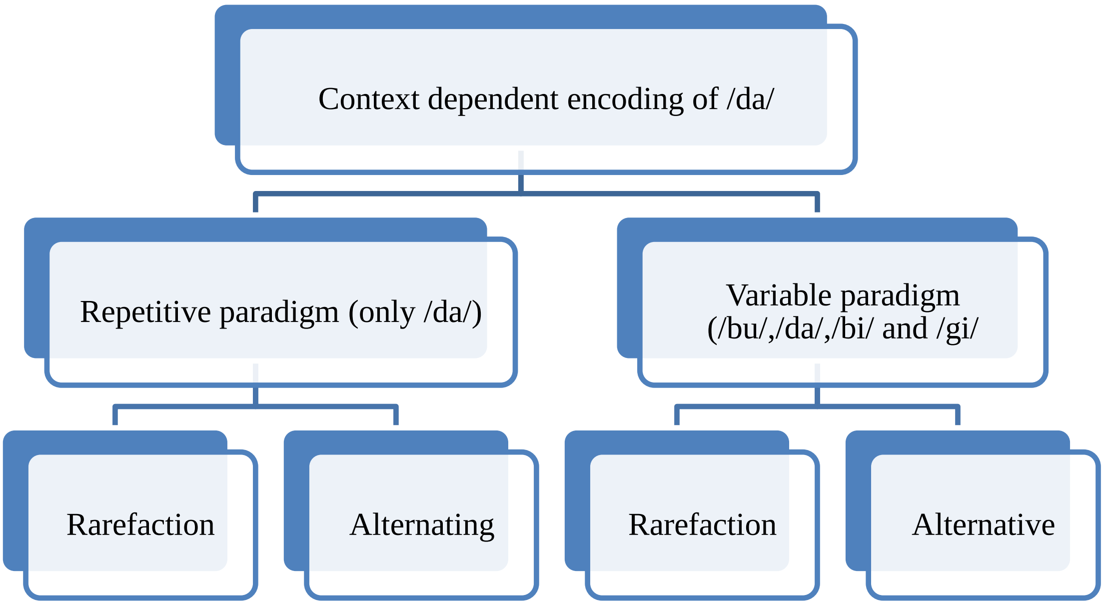

Figure 3.3: Representation of different stimulus conditions used in the present study.

3.4.3 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 FFRs. The averaged responses were subjected to spectral analysis to analyse the amplitudes at the spectral components corresponding to the fundamental frequency (H1 - 100 Hz), second harmonic (H2 - 200 Hz), third harmonic (H3 - 300 Hz) and fourth harmonic (H4=400) of the stimulus. This was done in a custom written program in Matlab 2014a platform developed at Northwestern University. The waveforms were windowed from 10 to 100ms using a 10% tapered Tukey window and zero-padded up to a total duration of 1s to increase the spectral resolution to 1Hz. The zero-padded waveforms were then subjected to FFT. The magnitudes at H1, H2, H3 and H4 were then analyzed by averaging the magnitudes of ten bins (1Hz wide) around the H1, H2, H3 and H4 frequencies. These spectral magnitudes were used as the index of brainstem encoding.

The data thus obtained was used for the comparison between repetitive and variable stim and the difference of the two was considered as the index of context dependent brainstem encoding. The so derived index was compared between the two stimulus polarities to verify the objectives of the study.

Chapter 4

RESULTS

The analysis of the data primarily focused on deriving the effects of polarity on the context-dependent encoding of speech. Stimulus polarity was treated as the independent variable and the measures of context-dependent encoding were the dependent variables. These measures were calculated by taking the difference in the amplitude of H1, H2, H3 and H4 of the frequency following responses (FFRs) recorded in repetitive and variable paradigms. Subsequently, the analysis also focussed on deriving the relationship between the measures of context dependent encoding elicited in the two polarities and the speech perception in noise (SNR-50). This was tested by correlating the two measures.

To begin with, the distribution of the data was tested using Shapiro Wilk's test of normality. The results normal distribution of the data (Appendix 1). Therefore, parametric tests such as, paired t-test, repeated measures ANOVA and Pearson's correlation. The results are reported in detail under the following explain the under the following headings:

1. Effect of stimulus paradigm and stimulus polarity on FFRs
2. Effect of stimulus polarity on the context dependent encoding in FFRs
3. Correlation between SNR-50 and the measures of context dependent encoding elicited in the two polarities.

4.1 Effect of Stimulus Paradigm and Stimulus Polarity on FFRs

In the study, FFRs were analyzed in terms of their amplitude in H1, H2 H3 and H4 regions. Table 4.1 gives the mean and standard deviation of H1, H2, H3 and H2 in the two paradigms (repetitive & variable), in the two polarities (alternating & rarefaction). The data showed that the mean H1 and H2 differed between the two paradigms while the mean H3 and H4 were same between the two paradigms. This was true in both the polarities.

Similarly, comparison of the amplitude of harmonics between the two polarities showed that the mean amplitude was same in most of the instances. The effect of stimulus paradigm and the stimulus polarity were statistically tested using repeated measures ANOVA. Table 4.2 shows the results of ANOVA which revealed that there was a significant main effect of the paradigm on all the four harmonics, whereas there was a significant main effect of polarity on only on H2 and H3. There was no significant interaction between effects of polarity and paradigm.

Table 4.1: Mean and standard deviation of H1, H2, H3 and H2 in the two paradigms (repetitive & variable), in the two polarities (alternating & rarefaction).

Measure	Paradigm	Alternating		Rarefaction	
		Mean (μV)	**SD**	**Mean (μV)**	**SD**
H1	Repetitive	0.05	0.02	0.05	0.02
	Variable	0.09	0.05	0.10	0.06
H2	Repetitive	0.03	0.01	0.03	0.02
	Variable	0.04	0.02	0.05	0.02
H3	Repetitive	0.02	0.01	0.02	0.01
	Variable	0.02	0.01	0.02	0.01
H4	Repetitive	0.01	0.009	0.01	0.004
	Variable	0.01	0.003	0.01	0.007

Table 4.2: Results of repeated measures ANOVA showing the effect of stimulus paradigm and polarity on the amplitude of four harmonics of FFRs.

Variable	Measure	F	p	Effect Size
Paradigm	H1	17.14	0.00	0.45
	H2	19.13	0.00	0.48
	H3	22.72	0.00	0.52
	H4	6.90	0.02	0.25
Polarity	H1	0.53	0.47	0.025
	H2	5.422	0.03	0.21
	H3	5.78	0.02	0.22
	H4	0.74	0.40	0.03
Paradigm* Polarity	H1	0.70	0.41	0.03
	H2	0.900	0.35	0.04
	H3	4.18	0.05	0.17
	H4	1.04	0.32	0.05

Note: df (error) was 1 (21).

Figure 4.1 shows the individual amplitude of H1 (A), H2 (B), H3 (C) and H4 (D) across the four stimulus conditions (2 stimulus paradigms * 2 stimulus polarities). It can be noticed from the figure that most of the participants showed higher amplitudes in variable paradigm compared to repetitive paradigm, irrespective of the stimulus polarity. However, no such trend was observed between the two polarities.

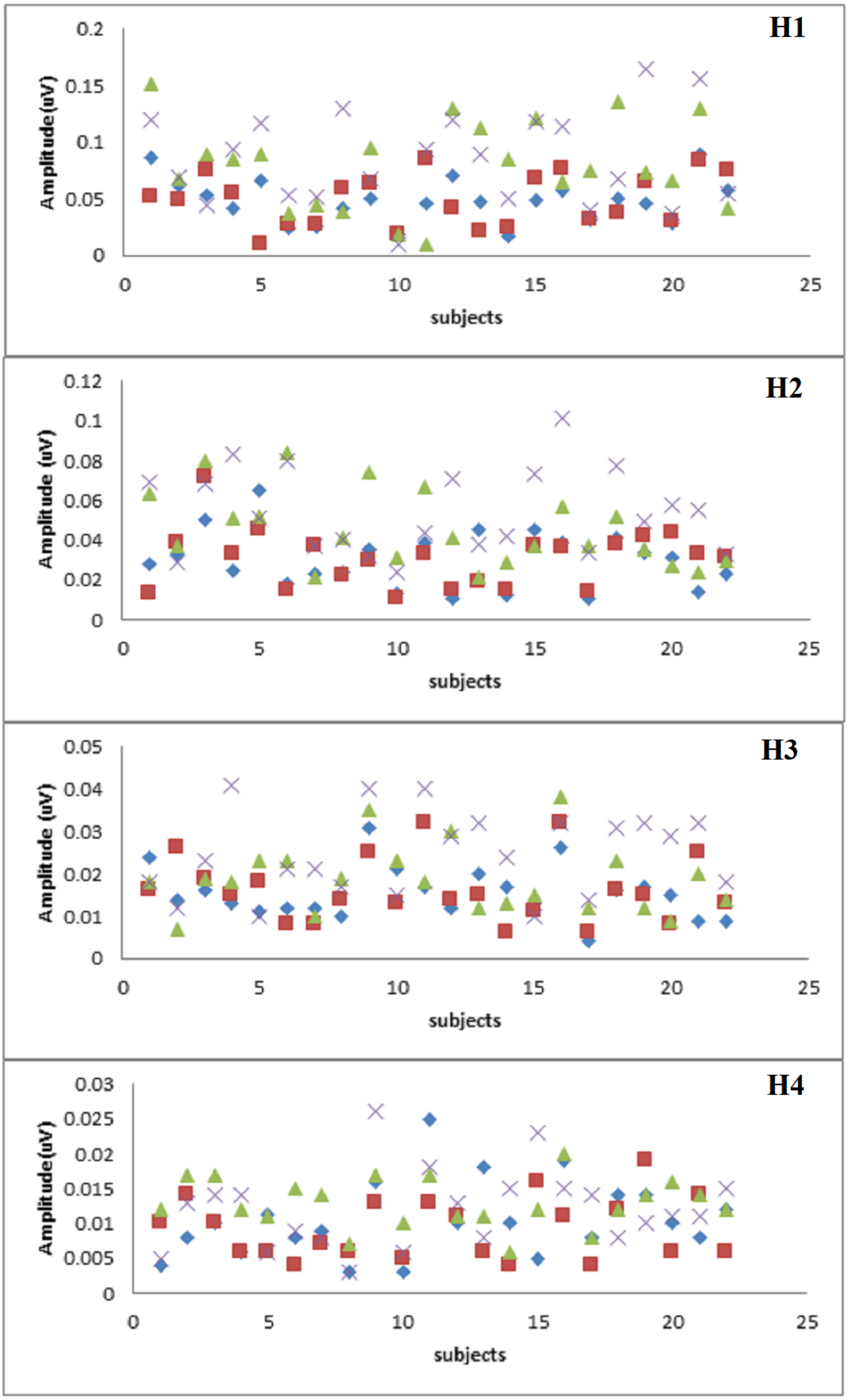

Figure 4.1: Individual amplitude of H1 (A), H2 (B), H3 (C) and H4 (D) across the four stimulus conditions (2 stimulus paradigms * 2 stimulus polarities). Repetitive alternative (♦), repetitive rarefaction (■), variable alternating (▲) and variable rarefaction (X).

4.2 Effect of Stimulus Polarity on the Context Dependent Encoding in FFRs

Context-dependent brainstem encoding was derived by subtracting the amplitude of H1, H2, H3 and H4 obtained in variable paradigm from that of repetitive paradigm. This was done separately for FFRs of rarefaction and alternating polarity. The difference amplitude was considered as the measures of context dependent encoding at each of the harmonics. Table 4.3 gives the mean and standard deviation (SD) of the measure at H1, H2, H3 and H4 obtained in the two polarities. The table also shows the results of paired t test comparing context dependent encoding between the two polarities. The results of t test showed that there was no significant difference between the two polarities in terms of their context dependent encoding.

Table 4.3: Mean and standard deviation (SD) of the measures of context dependent encoding at H1, H2, H3 and H4 obtained in the two polarities, and the corresponding t test results

Measure of context dependent encoding at	Polarity	Mean (uV)	SD	t	p
H1	Alternating	0.037	0.043	0.836	0.413
	Rarefaction	0.045	0.059		
H2	Alternating	0.014	0.021	0.948	0.354
	Rarefaction	0.021	0.027		
H3	Alternating	0.003	0.007	2.044	0.054
	Rarefaction	0.009	0.010		
H4	Alternating	0.002	0.007	1.019	0.320
	Rarefaction	0.004	0.007		

Note: df = 21.

4.3 Correlation between SNR-50 and the Measures of Context Dependent Encoding Elicited in the Two Polarities

In the study, SNR-50 was correlated with the context-dependent brainstem encoding obtained in the two polarities using Spearman's correlation test. The results are given in Table 4.4 which shows that there was no significant correlation between the measures of context dependent encoding and SNR-50. This was true with all the four harmonics and both the polarities.

Table 4.4: Results of Spearman's correlation test obtained by correlating measures of context dependent encoding and SNR-50, separately in the rarefaction and alternating polarities

Harmonic	**Polarity**	**Coefficient**	**p**
H1	Rarefaction	0.212	0.343
	Alternating	0.113	0.618
H2	Rarefaction	0.380	0.081
	Alternating	0.339	0.122
H3	Rarefaction	0.071	0.754
	Alternating	-0.049	0.828
H4	Rarefaction	-0.050	0.824
	Alternating	0.464	0.029

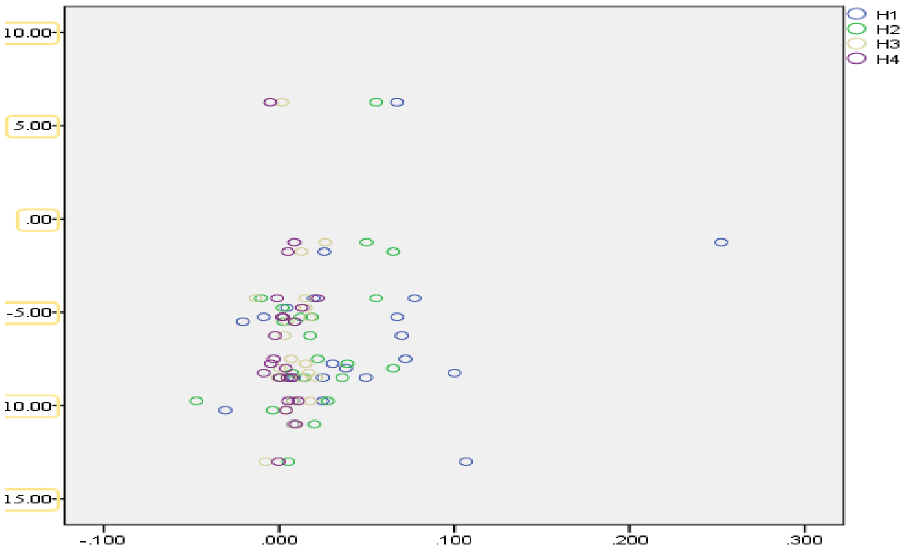

Figure 4.2: Scatter plot showing the relationship between SNR-50 in dB (y-axis) and harmonics in uV (x-axis) in rarefaction polarity.

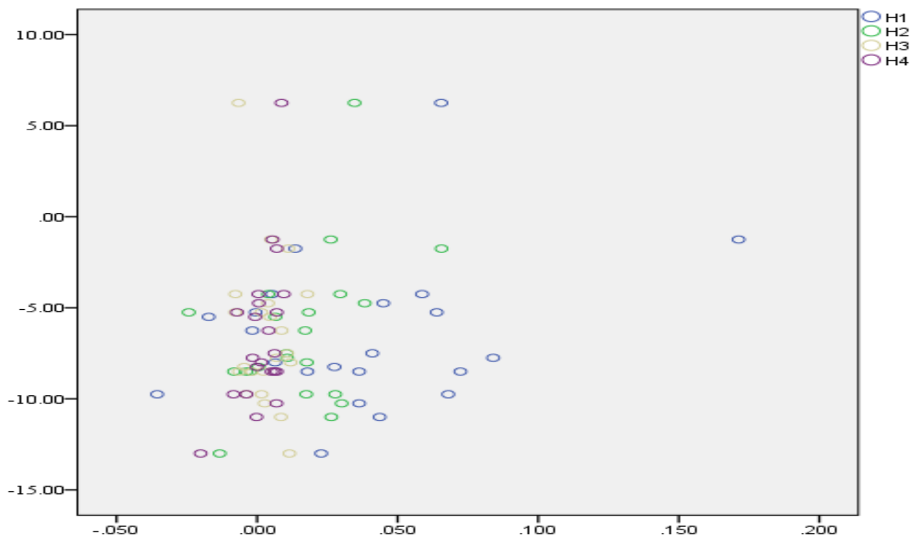

Figure 4.3: Scatter plot showing the relationship between SNR-50 in dB (y-axis) and harmonics in uV (x-axis) in alternating polarity.

Chapter 5

DISCUSSION

The primary aim of the study was to assess the effect of polarity on the context dependent encoding of speech, and influence of the polarity on its relationship with speech perception in noise. In the results, clear evidences for the presence of context dependent encoding were obtained. However, the study did not support for significant effect of stimulus polarity on context dependent encoding. The evidence to support the relationship between context dependent encoding of speech and speech perception in noise were also lacking in the study. The possible reasons for the results obtained, in light of the existing literature are discussed under the following headings:

1. Evidences for context dependent encoding of speech
2. Effect of stimulus polarity on the context dependent encoding
3. Relationship between speech perception in noise the context dependent encoding elicited in the two polarities

5.1 Evidences for Context Dependent Encoding of Speech

Auditory brainstem responses are shown to get fine tune based on the stimulus probability. Such context dependent differences in the brainstem physiology is attributed to the modulatory influence of the corticofugal pathway on the brainstem functions (Chandrasekaran., Hornickel, Skoe, Nicol, & Kraus., 2009; Maruthy, Kumar,& Gnaanateja 2017; Skoe & Kraus., 2010). The primary genratory of the frequency following responses being inferior colliculus and medial geniculate body, the modulatory influency of cortico fugal pathway is expected to determine the local neural activity in these regions. Such a modulatory influence is not attributal=ble to long term experience dependent neural plasticity (Chandrasekaran & Kraus., 2010; Strait, Hornickel & Kraus., 2011).

Typically, brainstem functioning is shown to get fine tuned with higher stimulus probability (Chandrasekaran et al., 2009; Maruthy, Kumar, & Gnaanateja 2017; Skoe & Kraus., 2010; Parbery-Clark, Strait & Kraus, 2011; Skoe & Kraus., 2010; strait et al. ,2011), which means FFRs in a repetitive paradigm would show higher spectral magnitude compare to variable paradigm. However, in the current study variable paradigm was found to result in higher spectral magnitude compared to repetitive paradigm. The finding is contradiction to most of the previous literature. But it is in agreement with Shruthi (2018). This means that the responses would be better when not repeated at regular interval. In Shruthi (2018) the finding was attributed to the difference in the stimulus polarity used. That is, Shruthi (2018) had used rarefaction polarity while all the previous studies was done using alternating polarity. Single and alternating polarities have been shown to differential record envelop and spectral following responses (Aiken & Picton., 2008; Povayya & Narne: 2013). While alternating polarity enhances envelope-following responses by suppressing spectral responses, vice versa happens in single polarity. Therefore difference in the result was attributed to the difference in the type of reference that are elicited and the differences in the corresponding influence of the context on the two type response.

The repetition induced suppression is typically seen in responses from the cortical regions. The earlier studies have shown P1 and N1 response to increase when spresented in the variable paradigm (Boutros, Gjini, Urbach & Pflieger, 2011; Malmierca, Sanchez-Vives, Escera & Bendixen, 2014). Recent studies have shown evidences for cortical contribution for the frequency following responses (Bidelman., 2018; Bidelman, Davis & Pridgen., 2018; Coffey et al., 2016: Coffey, Mussacchia & Zatorre.,2017). In view of the same, one can speculate that increased spectral amplitude in the variable paradigm is due to the involvement of the cortical regions. However, irrespective of the source of activity, the difference in the variable and repetitive paradigm shows a definite evidence for the involvement of the cortico-fugal pathway.

5.2 Effect of Stimulus Polarity on the Context Dependent Encoding

As stated earlier, Shruthi (2018) had found evidence of context dependent encoding with variable paradigm showing better responses than repetitive paradigm. This was in contradiction with all the previous studies, which had showed better responses for the repetitive paradigm. The difference in the results relative to the previous studies was attributed to the difference in the polarity used in their study compared to all the previous studies. The primary purpose of the present study was to scientifically verify whether the stimulus polarity would determine the type of context dependent encoding. Therefore in the present study, context dependent encoding was recorded for single as well as alternating polarity. Overall, the result revealed that there is no significant difference in the context dependent encoding obtained for single polarity as well as for alternating polarity. In both type of stimulus polarity it was found that the variable paradigm shows higher spectral amplitude than the repetitive paradigm. The results are partly in agreement with the Shruthi (2018), and it suggests that the difference found by Shruthi (2018) is not due to stimulus polarity.

In the absence of influence of stimulus polarity, the possible reason for variable paradigm being better than the repetitive paradigm could be attributed to the involvement of the cortical region in the generation of FFRs. Because cortical responses show repetitive induced suppression, repetitive paradigm may result in poorer response compared to the variable paradigm. The trend observed in the mean data is also very well supported by the trend in the individual data. In most of the participants, variable paradigm resulted in higher spectral magnitudes than the repetitive paradigm irrespective of the stimulus polarity.

It is also important to note that the responses elicited in alternating polarity are predominantly the envelope following responses. Whereas, the responses elicited in single polarity will have both envelope following and the spectral following responses. Despite, the pattern of context dependent encoding was same in both the polarities, indicating that irrespective of the type of the responses involved (spectral versus envelope), variable paradigm results in better spectral magnitudes compared to repetitive paradigm.

5.3 Relationship between Speech Perception in Noise the Context Dependent Encoding Elicited in the Two Polarities

Functionally, context dependent brainstem encoding has been shown to relate with speech perception in noise (Chandresekaran et al., 2009; Maruthy et al., 2017; Parbery-Clark et al., 2011: Strait et al., 2011). While Chandrasekaran et al. showed relation between the two in good and poor readers, Maruthy et al. showed evidence for it in comparison to the medial olivocochlear bundle. All these studies suggest that those with higher context dependent encoding are likely to show better speech perception in noise. However, the findings of the study do not show evidence for such a relationship. In the study there was no significant correlation between SNR-50 and the measures of context dependent encoding. Similar findings were reported by

Shruthi (2018). It is important to note that the protocol used for speech perception testing and the electrophysiological testing in this study is same as that of Shruthi (2018) and the findings are in total agreement with each other. In addition to procedure used by Shruthi (2018), the current study had tested the relationship between SPIN and context dependent encoding obtained in alternating polarity. The results were same in both the polarities.

One of the probable reasons attributed by Shruthi (2018) for the lack of correlation between SPIN and context dependent encoding in their study was the used of single polarity. However, the findings of the present study clearly rules out the role of stimulus polarity in determining the relationship between SPIN and the context dependent encoding. Maruthy et al. (2017) although had found the relationship between the two, the coefficient was low. The difference obtained could be attributed partly to the difference in the stimulus used for speech perception in noise. While the earlier studies had used the words and sentences, the current study and Shruthi (2018) had used monosyllables. Therefore, the role of redundancy of the stimulus used to test SPIN in determining the relationship between SPIN and context dependent encoding cannot be ruled out.

Chapter 6

SUMMARY AND CONCLUSIONS

Context dependent brainstem encoding derived through frequency following responses (FFRs) is an interesting phenomenon, shown to regulate speech perception in noise (SPIN). In an attempt to investigate the mechanism of context dependent encoding in the presence of noise, Shruthi (2018) had found lack of evidence for the relationship between speech perception in noise and context dependent encoding. One of the salient methodological difference that could possibly account for such a contradictory finding was the difference in the stimulus polarity used. Therefore, the present study primarily attempted to determine the effect of stimulus polarity on the context dependent brainstem encoding and its eventual relationship with speech perception in noise.

Twenty-two adults with normal auditory abilities participated in the study. Speech perception in noise in terms of SNR-50 was estimated from each of the participants. They were also subjected to recording of FFRs in four different stimulus conditions. FFRs were recorded for stimulus /da/ of 100ms in repetitive and variable stimulus paradigm. In the variable paradigm, FFRs were recorded in the context of /bu/, /bi/ and /gi/. FFRs in repetitive as well as variable paradigms were recorded by presenting the stimuli in rarefaction and alternating polarities.

FFRs were analysed using custom made toolbox to derive the spectral magnitudes at the first four harmonics (H1, H2, H3 & H4). Context dependent encoding was estimated by subtracting the spectral magnitudes obtained in variable paradigm from that of repetitive paradigm. The statistical analysis involved comparison of spectral magnitudes of the harmonics between variable and repetitive paradigms, and comparison of the measures of context dependent encoding between the two polarities. Parametric tests such as repeated measures ANOVA and paired t-test were used owing to the normal distribution of the data. Measures of context dependent encoding were also correlated with SNR-50 using Spearman signed rank test.

The results of the study showed that the variable paradigm resulted in higher spectral magnitudes of harmonics of FFR compared to that of repetitive paradigm suggesting context dependent brainstem encoding. This pattern of context dependent encoding was opposite compared to most of the previous studies, except Shruthi (2018). The results were same in both the stimulus polarities and there was no significant difference in the extent of context dependent encoding obtained in the two stimulus polarities. The results are discussed in light of the cortical contributions to the FFR and possibility of repetitive induced suppression in FFRs.

Furthermore, it was found that there is no significant correlation between SNR-50 and the measures of context dependent encoding. Context dependent encoding obtained in both the polarities showed lack of evidence for the relationship between the two. Therefore, the phenomenon of context dependent encoding needs a revisit and a thorough understanding of the factors affecting its relationship with SPIN is warranted.

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