Effect of Auditory and Visual Distractors on Brainstem Encoding of Speech

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CERTIFICATE

This is to certify that this dissertation titled **'Effect of Auditory and Visual Distractors on Brainstem Encoding of Speech'** is the bonafide work submitted as part fulfillment for the Degree if Master of Science in Audiology of the student with Registration No. 14AUD008. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other University for the award of any other diploma or degree.

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CERTIFICATE

This is to certify that this dissertation titled **'Effect of Auditory and Visual Distractors on Brainstem Encoding of Speech'** has been prepared under my supervision and guidance. It is also certified that this has not been submitted earlier to any other University for the award of any other diploma or degree.

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DECLARATION

This dissertation titled **‘Effect of auditory and visual distractors on brainstem encoding of speech’** is the result of my own study under the guidance of Dr. Sandeep M., Reader in Audiology, Department of Audiology, All India Institute of Speech and Hearing, and has not been submitted earlier to any other University for the award of any other diploma or degree.

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Acknowledgments

"We can only be said to be alive in those moments when our hearts are conscious of our treasures."

–Thornton Wilder

I am greatly indebted to my parents, teachers and many friends who paved the path before me in this journey and on whose shouders I stand today. This dissertation and the smile I wear is the result of all their support, sacrifices and inspirations.

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This dissertation is the culmination of a long journey built on friendship of countless fellow travelers, too numerous to list here. Thankyou all! Love!.

"Our life is like a journey: too even and easy and dull over long distances across the plains, too hard and painful up the steep grades; but on the summits of the mountain, you have a magnificient view and feel exalted and your eyes are full of happy tears and you want to sing and you wish you had wings! And then you cant stay there, but you must continue your journey"

- Lloyd C. Douglas

Thankyou for your part in my journey. God Bless!

ABSTRACT

The present study aimed to measure the effect of auditory and visual distractors on the brainstem encoding of speech. Speech ABRs were recorded in 31 normal hearing adults for synthetically generated /da/ presented to the right ear in four experimental conditions; Baseline, with meaningful auditory distractor stimulus, with non-meaningful auditory distractor stimulus and, with visual distractor stimulus. The transient response obtained was visually analyzed to note down the wave V latency, peak to trough amplitude and the slope. Frequency following responses (FFRs) were subjected to FFT to derive the magnitude of response at F0, H2, H3 and H4. Further, the spectrum of individual FFRs was extracted in the 1 Hz to 1000 Hz range and was compared across the four conditions. The results revealed that there is no main effect of condition on the latency, peak to trough amplitude and slope of wave V. However, the overall spectral magnitudes of FFRs were found to be inhibited in the presence auditory distractor as compared to baseline and visual distractor condition. When the auditory distractor was meaningful, the reduction of the spectral magnitudes was slightly higher compared to that in non-meaningful distractor condition. In the presence of the visual distractor, the overall spectral magnitudes of FFRs were observed to be higher than the baseline and auditory distractor conditions. The findings of the present suggest that brainstem encoding of speech is an active phenomenon. The corticofugal interaction elicited by the distractors seems to be either enhancive or inhibitory in nature based on the modality, type and difficulty of the task involved. Further, the activation of the corticofugal regulation is to some an extent influenced by the semantic load of the distractor stimuli.

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Chapter 1

INTRODUCTION

Auditory stimulus, while travelling from the peripheral to central structures is encoded at various levels which collectively determines perception of the sound. With specific reference to speech, brainstem encoding was considered to be a relatively passive process, while cortical processing was considered to be an active process. Such inferences about the brainstem encoding were primarily drawn using auditory evoked potentials elicited by clicks and tone bursts, while auditory brainstem responses (ABRs) generated for speech stimuli significantly changed this view. As the transmission and the coding of the speech are known to be more complex (Johnson, Nicol, & Kraus, 2005), auditory evoked potentials elicited for speech stimuli are likely to give a better insight on how the central auditory system processes speech sounds (Sinha & Basavaraj, 2010).

One of the several factors that influence auditory processing is attention. Selective attention is the ability to respond in a predetermined manner to only one or a small subset, from a number of equally potent stimuli (Eriksen & Hoffman, 1972). Most often selective attention enhances auditory perception by helping to focus on a sound of interest amidst irrelevant signals and is vital for survival (Bharadwaj, Lee, & Shinn-Cunningham, 2014). With respect to auditory selective attention, one of the most primary research questions has been whether selective attention modulates sound processing at the cortical level, or whether attention induced modulations take place at the level of sub-cortical auditory structures and cochlear structures also.

With respect to attention and cochlear functioning, results from the physiological studies reveal that selective attention (attending to one stimuli while ignoring another stimuli) modulates the functioning of the cochlear outer hair cells, thereby facilitating the processing of the target stimuli (de Boer & Thornton, 2007; Giard, Collet, Bouchet, & Pernier, 1994; Meric & Collet, 1992).

Over the past four decades researchers have explored the effect of attention on cortical event related potentials (Bidet-Caulet et al., 2007; Choi, Rajaram, Varghese, & Shinn-Cunningham, 2013; Hackley, Woldorff, & Hillyard, 1990; Hillyard, Hink, Schwent, & Picton, 1973). Hillyard and colleagues dichotically presented 2 similar series of tone pips and instructed participants to attend only to tones played to the designated ear (Hillyard et al., 1973). Comparison of the event related potentials to the attended and unattended revealed an enhanced N1 component to the former. Selective attention is also found to affect steady-state responses in the primary auditory cortex, and transient and sustained evoked responses in secondary auditory areas (Bidet-Caulet et al., 2007). The magnitude of the cortical exogenous and endogenous auditory evoked potential (Choi et al., 2013; Hackley et al., 1990) as well as ASSR (Keitel, Maess, Schröger, & Müller, 2013; Müller, Schlee, Hartmann, Lorenz, & Weisz, 2009) have been observed to increase when subjects were actively listening to an auditory stimulus compared to when they perform a visual task or are ignoring the same auditory inputs. Kadobayashi and Toyoshima (1984) reported no significant effect on latency but significant reduction in amplitude of the early portions of middle latency potentials to binaural 50 dB SL clicks, during attention.

Gregory, Heath, and Rosenberg (1989) compared click evoked BAEPs elicited during visual attention and during auditory attention, but did not find any effect of attention on wave I, II, III, IV and V latencies or amplitudes. Similar results have been reported by Gutschalk, Micheyl, and Oxenham (2008). Several studies have probed into the effect of attention on Frequency Following Responses (FFRs). Galbraith and colleagues probed into the effect of attention on FFRs elicited by pure tones (Galbraith & Arroyo, 1993; Galbraith & Doan, 1995), English long vowels (Galbraith, Bhuta, Choate, Kitahara, & Mullen, 1998) and complex tones (Galbraith, Olfman, & Huffman, 2003). They reported increased FFR amplitudes in the attended condition as compared to the unattended condition and this increase in amplitude was prominent in auditory attention tasks as compared to visual attention tasks. Based on the findings they concluded that brainstem processing is modulated by attention and they attributed it to the corticofugal pathways. In contrary, Galbraith and Kane (1993) and Varghese, Bharadwaj and Shinn-Cunningham (2015) reported no significant effect of auditory and visual attention on FFRs.

There ample anatomical evidence for the existence of corticofugal connections to the sub-cortical structures including the brainstem (Suga, Gao, Ma, Sakai, & Chowdhury, 2001; Terreros & Delano, 2015; Winer, 2006). In animals, efferent projections from auditory cortex play a role in the long-term plasticity of the neural firing properties of a number of different subcortical structures, including outer hair cells (Suga, Xiao, Ma, & Ji, 2002), cochlear nucleus, superior olivery complex (Palmer & Rees, 2010), neurons in inferior colliculus (Bajo, Nodal, Moore, & King, 2010; Yan & Suga, 1996), and possibly at later sub-cortical processing stages as well. In humans, Lukas (1980) investigated the effect of attention on click evoked ABRs and reported a decrease in the inter-peak latency. Other studies have reported that the amplitudes of ASSRs are modulated by both inter-modal attention (Keitel, Maess, Schröger, Müller, & Met, 2013) and selective auditory attention (Bharadwaj, Lee, & Shinn-Cunningham, 2014; Linden, Picton, Hamel, & Campbell, 1987). Selective attention is also known to influence envelope following responses (Lehmann & Schönwiesner, 2014).

1.1 Justification for the Study

As reported by Chandrasekaran and Kraus (2010) and Chandrasekaran, Skoe and Kraus (2014) there is evidence for existence of continuous, online modulation of brainstem encoding by the auditory cortex via corticofugal pathways in humans and they termed it as online plasticity (Chandrasekaran, Krishnan, & Gandour, 2007). This online plasticity is known to regulate the way brainstem encodes speech based on the stimulus statistics, which suggests that brainstem encoding of speech is not a passive function as understood with click evoked ABRs. Functionally, the online modulatory mechanism is found to regulate speech perception in noise (Strait, Kraus, Parbery-Clark, & Ashley, 2010). Considering that the brainstem processing is not a passive process, one could expect that a competing signal delivered to the opposite ear will influence the brainstem encoding of speech. In the presence of a distracting stimulus, the influence of corticofugal pathway may vary and thereby lead to differences in the speech ABR. In such a case, one would also be curious to attempt to understand whether a distractor in the auditory domain versus a distractor in the visual domain would have the same influence. However, till date there are no studies that have probed into the effects of distracting stimulus on the brainstem encoding of speech. The findings of such a study would throw light on the mechanisms of corticofugal modulation and brainstem encoding. Therefore the present study was taken up.

1.2 Aim of the Study

The present study aimed to investigate the effect of distractors on the brainstem encoding of speech.

1.3 Objectives of the Study

The objectives of the present study were:

1. To test the effect of auditory and visual distractors on onset and sustained brainstem responses elicited by /da/
2. To compare the effect of meaningful and non-meaningful auditory distractors on onset and sustained brainstem responses elicited by /da/

Chapter 2

REVIEW OF LITERATURE

The primary function of the auditory neural pathway is to transmit and encode the input it receives from the cochlea to the higher order structures in the pathway. The representation of an auditory signal at the level of brainstem can be captured reliably by recording the evoked brainstem responses (Musacchia, Sams, Skoe, & Kraus, 2007). These responses are time locked neural representations of the stimulus recorded from a far field (Krizman & Kraus, 2010).

A variety of stimuli such as clicks, tones and speech stimuli have been used to elicit auditory brainstem responses (ABRs). However, the clicks or tone evoked responses do not truly represent the way brainstem codes complex speech sounds. Hence, responses elicited using speech stimuli were thought to be a better choice to probe into how the central auditory system encodes and transmits speech sounds (Sinha & Basavaraj, 2010; Skoe & Kraus, 2010a). The ABR response elicited using a speech stimulus was termed as ‘speech evoked ABR’.

2.1 Speech Evoked ABR

A variety of speech stimuli such as vowels (Aiken & Picton, 2008), consonant vowel transition (Akhoun et al., 2008; Banai et al., 2009; Plyler & Ananthanarayan, 2001; Russo, Nicol, Musacchia, & Kraus, 2004), speech syllables (Hornickel, Skoe, & Kraus, 2009) and words (Galbraith et al., 2003) have been used to evoke speech ABRs. The responses elicited closely resembles the stimulus such that, if played back, the recorded sound can be identified as the input stimulus (Galbraith & Doan, 1995).

In the past a plethora of studies have probed into how the brainstem responds to speech syllable /da/ (Banai et al., 2009; Banai, Nicol, Zecker, & Kraus, 2005; Chandrasekaran, Hornickel, Skoe, Nicol, & Kraus, 2009; Cunningham, Nicol, Zecker, Bradlow, & Kraus, 2001; Hornickel, Skoe, Nicol, Zecker, & Kraus, 2009; Johnson, Nicol, Zecker, & Kraus, 2007; King, Warrier, Hayes, & Kraus, 2002; Kraus & Nicol, 2005; Russo et al., 2004; Song, Skoe, Wong, & Kraus, 2008; Wible, Nicol, & Kraus, 2004). The rationale behind preferring /da/ over other speech syllables is its universal nature, the inherent property that it has a transient followed by a sustained portion, and its ability to elicit replicable and clear responses (Skoe & Kraus, 2010a). This led to the development of the BioMARK /da/ (Biological Marker of Auditory Processing, Natus Medical Inc.).

Similar to most of the studies in the literature, the stimulus used in the present study is a synthetic BioMARK /da/ of 40ms. The brainstem response to /da/ is composed of an onset portion which codes the unvoiced burst onset and is composed of peaks similar to that seen in click evoked ABRs (waves V followed by a negativity A). Following the transient portion a sustained portion (FFR) is seen in the response and it codes the F0 and its harmonics (see Figure 2.1).

On the arrival of a stimulus, neurons at the level of brainstem phase-lock to the periodic variations in the temporal fine structure and codes the transition as well as the short vowel portion which follows it (Musacchia et al., 2007; Skoe & Kraus, 2010). Moushegian, Rupert and Stillman (1973) studied the sustained brainstem responses using sinusoids ranging from 250 Hz to 2 kHz and they reported that the responses mimic the time locked neural discharge to the temporal structure of the eliciting stimulus. Further they reported that FFRs can be recorded for stimulus frequencies as high as 1.5 kHz and the phase locking becomes weaker with increasing frequency due to the low-pass nature of brainstem phase locking. Hence it can be inferred that speech elicited ABR taps the precision of temporal processing at the level of brainstem (Greenberg, Marsh, Brown, & Smith, 1987; Johnson, Nicol, & Kraus, 2005; Moushegian et al., 1973; Russo et al., 2004).

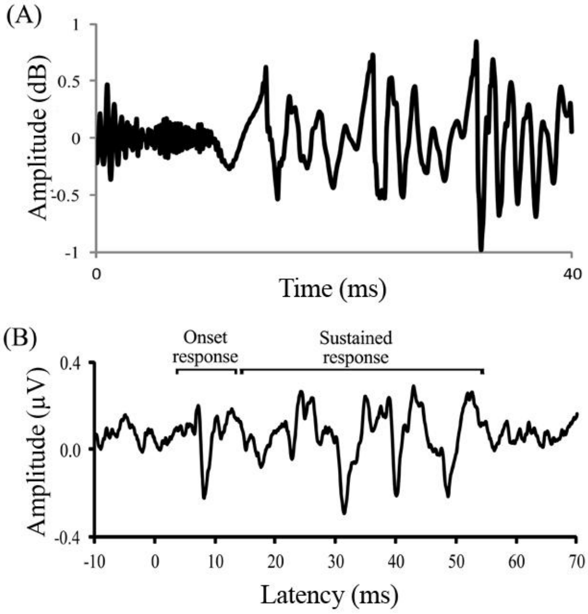

Figure 2.1: The BioMARK /da/ stimulus (A), the transient and sustained response elicited by /da/ (B).

The transient portion and the sustained FFR portion have been reported to be originating from different neuronal populations within the central auditory nervous system (Chandrasekaran & Kraus, 2010). Based on the latency and morphology of the onset response to /da/ (5-10 ms), they suggested that the generators of the onset response /da/ and click evoked response are same and can be traced to the brainstem. With respect to the generators of sustained FFRs, Galbraith et al. (1994) reported that using a horizontal electrode montage captures the activity of caudal brainstem neurons (cochlear nucleus) and vertical electrode montage captures the activity from the rostral brainstem structures such as the lateral lemniscus or inferior colliculus.

2.2 Brainstem Encoding of Speech: Active vs. Passive Process

A passive process may be defined as a series of open loop events by which there is un-modulated mapping from the input to the output (MacKay, 1951). This essentially maintains that the input received by auditory nerve is directly transmitted via the higher order neuronal populations in brainstem to the auditory cortex and is not influenced by processing outside this circuitry (Heald & Nusbaum, 2014). Until recently the brainstem processing of speech was thought to be a passive process with no role of a feedback loop which modulates the processing. However recent literature based evidence suggests that this is not true, and that the speech processing at the level of brainstem is an active process influenced by experience in a particular language or music (Musacchia et al., 2007), inputs from other sensory modalities (Meric & Collet, 1992) and selective attention (Galbraith et al., 2003). Hence, active processing involves feedback loops that in real time modifies or corrects the processing in the brainstem.

Recent studies have reported that brainstem processing of speech is malleable (Chandrasekaran & Kraus, 2010; Song et al., 2008). Skoe, Chandrasekaran, Spitzer, Wong, and Kraus (2014) reported that two types of plasticity occur at the level of brainstem: long-term learning/experience dependent plasticity and short-term probability based plasticity. Krishnan, Xu, Gandour and Cariani (2005) studied the effect of language experience on brainstem representation of speech. They reported that, when compared to native English speakers, the ability of brainstem to track the changes in F0 (phase locking) of Mandarin (tonal language) tones is better in native Mandarin speakers. This suggests that pitch encoding at the level of brainstem is influenced by language experience. Similar results have been reported by Krishnan, Swaminathan and Gandour (2009). They reported that FFRs of Mandarin speakers had comparatively stronger representation of multiple pitch-relevant harmonics compared to the non-native group. They attributed this finding to the long-term experience of the Mandarin speaker in tonal language which led to an enhancement in the FFR spectrum. Russo, Nicol, Zecker, Hayes, and Kraus (2005) recorded /da/ elicited ABR in quiet and in noise. The recordings were done before and after 3 months of auditory training. Results revealed that post training subjects exhibited brainstem responses that were more resistant to effects of noise. Song, Skoe, Wong and Kraus (2008) probed into the neural plasticity by recording FFRs, following short-term linguistic training. They again reported enhanced FFRs post-training and the plasticity effect was found to be specific only to the stimuli they received training in.

With respect to music experience, Musacchia et al. (2007) reported that in musicians, brainstem responses to both speech and music were more robust and occurred at latencies earlier than in the control group in the auditory only condition as well as in the audio-visual condition. They concluded that practice led to enhanced phase locking to periodicity of the stimulus in musicians. They also probed into the effect that addition of a visual input has on the brainstem encoding of speech stimulus /da/. The results of the study revealed that when a visual stimulus (speaker uttering /da/) is played along with speech stimulus, the amplitude of the response spectrum around the F0 region was found to be higher compared to the auditory stimulus only condition. This enhancement was found to be more for the musicians compared to the non-musician control group. This shows that musical training induced plasticity modulates the processing at the level of brainstem in trained musicians. Parbery-Clark, Skoe, and Kraus (2009) tested the effect of musical experience on the neural representation of speech in noise. Speech ABR elicited by /da/ of 170 ms was recorded in quiet and in noise. The participants consisted of highly trained musicians, and non-musician controls. Results revealed that musicians have better temporal phase locking, enhanced spectral information and better wave morphology in noise compared to the non-musician controls suggesting that musical experience leads to superior neural encoding at the level of brainstem in the presence of noise.

Galbraith et al. (2003) probed into the effect of selective attention on FFRs. FFRs were recorded for complex tonal stimulus while the subjects were required to detect infrequent target stimulus in the auditory or visual domain. The results revealed that when the subject attended to infrequent target in the auditory domain, a significant difference in the FFR amplitude was present. However, differences are not present for the visual infrequent stimulus.

Chandrasekaran, Hornickel, Skoe, Nicol, and Kraus (2009) reported the ABRs elicited by syllable /da/ demonstrated larger sustained response when it is presented in a repetitive and predictable context when compared to same sound presented randomly. They observed that the local sound statistics (repetition) interact and continuously refine the brainstem processing (short term plasticity). Skoe, Chandrasekaran, Spitzer, Wong, and Kraus (2014) tested the training induced brainstem plasticity. The experiment procedure involved baseline speech ABR assessment followed by 9-session pitch-pattern training programme and a retest. The results revealed that the pitch encoding was superior for frequently presented stimuli than the infrequently presented stimuli and hence attributed enhancement to the effect of probability.

These results suggested that the brainstem processing of speech is a malleable phenomenon which is brought about by a feedback from the cortex via the extensive corticofugal pathways, locally initiated changes in the brainstem or due to a combination of both (Skoe & Chandrasekaran, 2014).

2.3 Cortico-fugal Efferent Projections

The mammalian neuro-auditory pathway can be divided into the afferent (ascending) and the efferent (descending or corticofugal) pathways. The afferent pathway delivers the sound from the peripheral auditory structures to the auditory cortex. Parallel to the afferent pathways run the descending corticofugal projections from the auditory cortex and extend till the organ of corti in the cochlea (Malmierca & Ryugo, 2011). The existence of the corticofugal tract was first reported in literature towards the end of 19th century (Malmierca, Anderson, & Antunes, 2015). However, until recently the possibility of a cortical-subcortical interaction via the corticofugal pathways was not probed into (Suga, Gao, Zhang, Ma, & Olsen, 2000).

Recent literature suggests that the corticofugal pathways modulate the processing of auditory signal at the level of subcortical structures by evoking short-term changes in the subcortical auditory nuclei (Suga, Xiao, Ma, & Ji, 2002; Winer, 2006). The fibres from the auditory cortex project to a range of subcortical structures of the auditory pathway (Malmierca et al., 2015). The corticofugal pathway comprises of neurons originating in the primary auditory cortex and projecting to the medial geniculate body, inferior colliculus, superior olivary complex and cochlear nucleus (Figure 2.2). The Superior olivery complex communicates with cochlea through the olivocochlear bundle (Terreros & Delano, 2015). The corticofugal fibers to medial geniculate body are present ipsilaterally and projections to inferior colliculus, superior olivery complex and cochlear nucleus are present bilaterally. However, the ipsilateral projections are more extensive and tonotopically organized than the contralateral projections (Suga et al., 2001). The presence of such large corticofugal fibre tracts suggests that responses of neurons in these structures could be influenced by cortical activity (Nuñez & Malmierca, 2007; Saldaña, Feliciano, & Mugnaini, 1996; Winer, Larue, Diehl, & Hefti, 1998).

Malmierca et al. (2015) studied the corticofugal connections to medial geniculate body and inferior colliculus by recording single neuron responses from medial geniculate body before and after deactivating the auditory cortex by cooling. Their results revealed that properties of the medial geniculate body and inferior colliculus neurons such as frequency response, spontaneous activity and latencies were altered, suggesting that medial geniculate body, inferior colliculus and other subcortical nuclei receive corticofugal connections. These corticofugal driven modulations of the subcortical structures might in turn modify the ascending information transmitted via the afferent neural tract. He (2003) reported that corticofugal pathway induced gain control process lead to enhanced coding of the relevant stimuli, and might possibly underlie auditory attention.

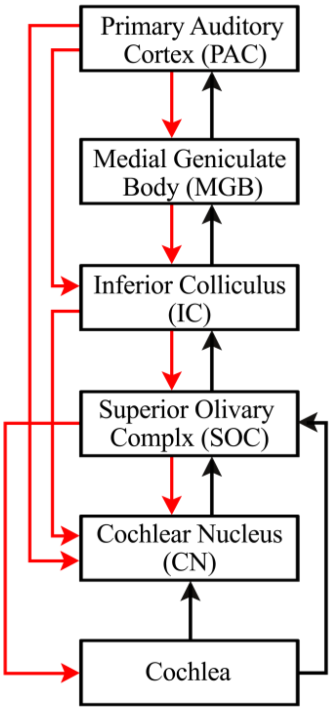

Figure 2.2: The central auditory pathway (red lines represent corticofugal pathway and the black lines represent efferent pathways).

The terminal effect of the cortical neurons on the sub-cortical neuronal population facilitated by the corticofugal interaction can be either facilitatory, inhibitory or both (Nuñez & Malmierca, 2007; Suga et al., 2000). Based on immunohistopathological evidence, Nuñez and Malmierca (2007) suggested that L-glutamate is the facilitatory/excitatory neurotransmitter in the corticofugal pathway and there is ample of evidence for the inhibitory effect as well. Suga et al. (2000) reported that the neurons are tuned to a particular best frequency. The amount of facilitation or inhibition depends on the frequency tuning between the stimulated and the recorded neuron. Facilitation is observed in case of matched neurons while inhibition is reported in the unmatched regions (Nuñez & Malmierca, 2007; Yan & Suga, 1996). Hence the frequency response near the best frequency is sharpened and outside the best frequency response is inhibited. This phenomenon has been termed as egocentric selection (Heald & Nusbaum, 2014; Suga et al., 2002).

When acoustic stimuli is delivered to the auditory system, they are converted to the neuronal representation and transmitted from the cochlea to the primary auditory cortex. Then an egocentric selection is initiated by the primary auditory cortex and the corticofugal system which is executed as a small, short-term modulation of the signal processing at the sub-cortical level (Hillyard, Vogel, & Luck, 1998; Nuñez & Malmierca, 2007; Suga et al., 2000; Terreros & Delano, 2015; Yan & Suga, 1996). Hairston, Letowski, and McDowell (2013) reported that on addition of a task, the attentional load within the cortex increases. This leads to simultaneous activation of the corticofugal pathways which in turn facilitates or inhibits the encoding clarity at the level of brainstem and is reflected as enhancement or suppression of spectral magnitudes in the FFRs. They also reported that, addition of a task in the same domain (as in addition of an auditory attention task while assessing AEP) further increases the cortical load. The cortical neurons respond to this by increasing the corticofugal modulation which reflects as a change in the spectral magnitude.

2.4 Attention and Auditory Brainstem Responses

Attention involves selective awareness of certain sensory messages with the simultaneous suppression of others (Hernandez-Peon, Scherrer, & Jouvet, 1956). Attention has been reported to function as a gain control mechanism. It provides higher gain in the attended channel and provides comparatively less gain in the unattended channel (Lee, Larson, Maddox, & Shinn-Cunningham, 2014).

One of the pioneer reports with respect to effect of attention on a brainstem nucleus is the one by Hernandez-Peon et al. (1956). They reported a reduction in amplitude of cochlear nucleus responses in cats compared to when no attention task was given. This reduction in amplitude was evident when both visual and olfactory stimuli were presented. Hence they concluded that the response to an auditory input at the level of cochlear nucleus is inhibited by a sensory input in another modality. Later, Berlin et al. (1993) explained this finding stating the possibility of olivocochlear bundle or corticofugal fibers in altering the function of brainstem nuclei as early as at the level of cochlear nucleus.

With respect to the effect of attention on ABRs in humans, Picton and Hillyard (1974) studied whether attending to the click stimulus has an effect on the click evoked ABRs. In the unattended condition the subjects were required to read a book to keep their attention away from the click stimulus. They reported no significant effect of attention on the amplitude or latency of ABR waves I-VI. In a similar study, Lukas (1980) recorded ABRs elicited by tone pips in two trials. In the first trial the participants had to listen to the tone pips and in the second trial they were required to mentally count visual stimuli. The results revealed that in the visual attention condition, latency increased and amplitude decreased for wave V. This effect was attributed to the functional role of olivo cochlear bundle which suppressed the irrelevant stream. Papanicolaou, Raz, Loring, and Eisenberg (1986) used speech production as an attention modality. Click evoked ABRs were recorded when subjects had to do speech production tasks and they found out a significant reduction in wave V amplitude during normal speaking and whispering tasks which was attributed to efferent inhibition. However, later reports reveal no effect of visual and auditory attention on wave I, II, III, IV and V latency, amplitude and wave I-V interval for click evoked ABR (Gregory, Heath, & Rosenberg, 1989) and tone burst evoked ABRs (Kuk & Abbas, 1989). Gregory et al. (1989) recorded click evoked ABRs during visual and auditory attentional tasks and reported no effect of attention on latency of wave I, wave I-V inter peak-latency and the amplitudes of waves I and V. Kuk and Abbas (1989) also probed into the effect of attention on tone burst evoked ABR. The attention tasks consisted of visual duration discrimination task or frequency discrimination task in the auditory modality. They reported no effect of attention on the morphology and latencies of the waveforms obtained in different experimental conditions and concluded that attention demand does not influence the auditory efferents.

The FFR is a component of the auditory brainstem response arising from the phase locking properties of the neurons at the level of rostral brainstem and it closely replicates the eliciting stimulus. This makes FFR an appropriate tool to study the representation of the sound at the level of brainstem (Hairston, Letowski, McDowell, & Kaleb, 2013). The earliest report on effect of attention on FFRs is by Galbraith and Arroyo (1993). The results of the study revealed a significant effect of attention on pure tone (200Hz & 400Hz) evoked FFR and hence they suggested presence of a peripheral gating mechanism in humans. Followed by this, they extended the research by probing into effect of attention on FFR and cortical event related potential elicited by a 230 Hz pure tone (Galbraith & Kane, 1993). They reported a significant increase in amplitude in event related potentials when the subjects attended to the eliciting stimuli. However, contradictory to their earlier study (Galbraith & Arroyo, 1993) they did not find any significant difference in FFR elicited in the attended and unattended condition. Galbraith and Doan (1995) studied the effect of attention on FFR elicited by 400Hz pure tone and missing fundamental stimuli presented dichotically. The subjects were required to detect infrequent target stimuli (presented in either ear) which were either of lower intensity or greater duration than the FFR eliciting stimuli. They reported an increase in FFR amplitude in the attended channel compared to the unattended channel for both the stimuli and during both the tasks. Later Galbraith et al. (1998), studied the role of attention on FFRs elicited by English long vowels /a/ and /e/ recorded from a female and male speaker respectively. They reported larger F0 amplitudes when the vowels were attended suggesting that attention modulates the brainstem processing of speech sounds.

Galbraith et al. (2003) probed into the effect of selective attention on FFRs. FFRs were recorded for complex tonal stimulus while the subjects were required to detect infrequent target stimulus in the auditory or visual domain. Significant increment in FFR amplitudes was observed only for infrequent stimulus in the auditory domain and not for the visual domain. In a functional MRI study, Rinne et al. (2008) examined the activation of inferior colliculus in humans during auditory attention tasks. Participants were required to selectively attend to stimuli presented in the left or right ear while ignoring the stimuli in the other ear. They reported significant changes in the inferior colliculus when participants attended to the pitch tracking tasks suggestive of top-down modulation mediated via the corticofugal pathways.

Hairston et al. (2013) conducted an experiment as part of which FFRs elicited by a 220Hz sinusoid was recorded binaurally while the participants performed a visual and auditory temporal discrimination task. The recorded responses in the two task conditions were compared with FFRs elicited when no task was performed (control condition). It was found that the addition of task led to decreased signal clarity and this reduction was found to be significantly high for task in the auditory mode. Lehmann and Schönwiesner (2014) presented vowels /a/ and /i/ recorded from a male and female speaker respectively to elicit FFRs. The vowels were presented dichotically and the participants were required to selectively attend to the male /a/ or female /i/ as instructed. They reported enhanced FFR amplitude in attended condition as compared to unattended condition. However, a recent study by Varghese, Bharadwaj and Shinn-Cunningham (2015) reported no significant differences in brainstem steady state responses while participants completed attention tasks such as monoaural listening, selective attention during dichotic presentation and visual attention tasks.

Hence from the close examination of the existing literature it may be inferred that attention influences the brainstem processing as revealed by ABRs elicited by clicks and FFRs elicited by tones and vowels. However, contradictory reports have also been published with respect to ABRs (Gregory et al., 1989; Hillyard et al., 1973; Kuk & Abbas, 1989) as well as FFRs (Galbraith & Kane, 1993; Varghese et al., 2015). The inherent property of speech is that its acoustic properties vary as a function of time and this information is missed out while using clicks, tones or steady state vowels to elicit speech ABRs. Using a consonant vowel syllable will give a better picture about how the brainstem encodes onset, transitions, vowels and offsets (Archana, Kishan, Kumar, Rajashekhar, & Prakash, 2015). Furthermore, previous studies have not probed into the effect of semantic content of a distractor on the subcortical encoding of speech. Given that semantic analysis is a higher order cortical event (Mitchell & Cusack, 2016; Wirth et al., 2007) and given that there exists top-down modulation mediated via corticofugal pathways, the need of present study is warranted.

Chapter 3

METHOD

The present study used repeated measures research design to test the effect of auditory and visual distractors on onset and sustained brainstem responses elicited by /da/. The null hypothesis in the present study was that there is no significant effect of meaningful auditory distractors, non meaningful auditory distractors and visual distractors on brainstem encoding of speech. The following method was adopted to test the hypothesis.

3.1. Participants

Thirty one adults, comprising of 12 males and 19 females, in the age range of 18 to 24 years (Mean age of 21.3 years) participated in the study. All the participants had normal hearing with pure tone thresholds being 15dBHL or lesser at octave frequencies between 250 Hz and 8000 Hz. They had normal middle ear functioning as tested on immittance evaluation. The participants had type A or As tympanogram with acoustic reflexes present in both the ears. Transient evoked oto-acoustic emission was used to rule out outer hair cell dysfunction. All the participants had signal to noise ratio (SNR) of more than 6dBSPL in at least 3 consecutive octave frequencies. The participants were screened for auditory processing disorders using Screening Checklist for Auditory Processing in Adults (Vaidyanath & Yathiraj, 2014). All the participants had intact neural pathway at the level of brainstem as revealed by click ABRs. None of them had any past or present history of otological and neurological dysfunction. All the participants were students of bachelors or masters academic programme at AIISH, Mysuru. They were native speakers of Kannada and had learnt

English as their second language. The participants were also proficient in using numeric keypad of computer.

Prior to the testing, details regarding the objectives of the study and procedure involved was explained and an informed written consent was obtained from all the participants in line with the institutional guidelines.

3.2. Instrumentation

The following equipments were used in the present study

1) A calibrated two channel diagnostic audiometer, GSI-61 (Grason-Stadler Incorporation, USA) paired with Telephonics TDH 39 supra aural headphones and Radio ear B-71 bone vibrator was used for hearing threshold estimation and speech audiometry.
2) A calibrated GSI-tympstar (Grason-Stadler Incorporation, USA) clinical immittance meter, calibrated as per ANSI (1987) was used for tympanometry and reflexometry.
3) Calibrated ILO 292 DP Echo port system (Otodynamics Inc., UK) was used to record transient evoked oto-acoustic emissions.
4) Adobe Audition 3.0 (Adobe Systems Inc) installed on a Dell Inspiron 15 3000 series laptop (Realtek sound card) with AHUJA AUD- 101XLR dynamic unidirectional microphone was used for recording the auditory stimuli and presenting the distractor stimuli.
5) Calibrated Biologic Navigator Pro EP system (Natus Medical Inc., Mundelein, USA) was used to record auditory brainstem responses.

6) A numeric keypad connected to the laptop was used for the participants to register their task specific responses.

3.3. Stimulus

Two types of stimuli were used in the present experiment; stimulus for eliciting ABR and the distractor stimuli.

3.3.1 Stimulus for eliciting speech ABR

In the present study, ABRs were elicited by syllable /da/ of 40ms duration. This syllable was the default stimulus of the BioMARK module in the Biologic navigator Pro system. It was synthesized using KLATT synthesizer and had 5 formants (Krizman & Kraus, 2010; Skoe & Kraus, 2010). The F0 ranged from 103 Hz to 125 Hz, F1 from 220 Hz to 720 Hz, F2 from 1700 Hz to 1240 Hz and F3 from 2580 Hz to 2500 Hz. F4 and F5 are constant at 3600 and 4500 Hz, respectively.

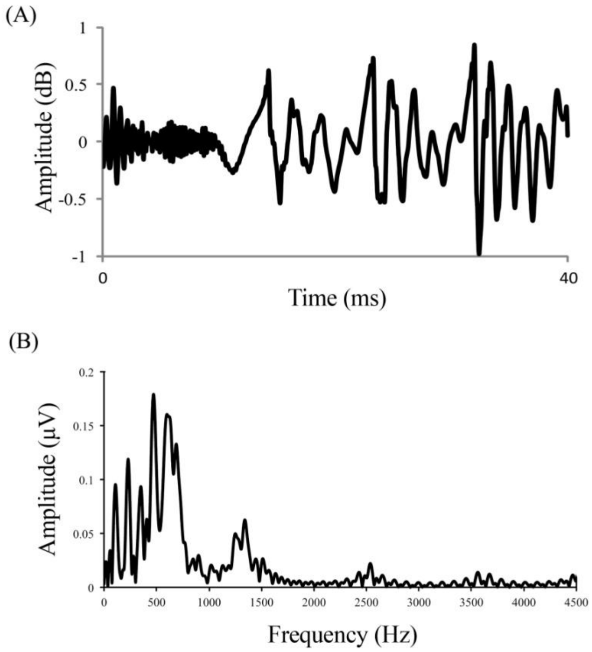

Figure 3.1: The waveform (A) and the spectrum (B) of the syllable /da/ used in the present study.

The stimulus had an onset burst frication of 10ms followed by 30ms of formant transition. It did not have steady state portion of the vowel. The waveform and spectrum of the syllable /da/ used in the present study are given in Figure 3.1A and Figure 3.1B respectively.

3.3.2 Distractor Stimuli

Three types of distractor stimuli were used in the present study. They differed in terms of modality and/or meaningfulness. In terms of modality, distractors were used in the auditory and visual modes. Meaningfulness was manipulated only for the distractors in the auditory modality. Whereas all the distractor stimuli presented in the visual modality were meaningful. The details of the three distractor stimuli used in the present study are given below.

1) ***Meaningful Auditory Distractor (MAD) Stimulus:*** One hundred and twenty English words were selected from 4 lexical categories (animals, professions, common objects & fruits/vegetables) with each lexical category having 30 words.

   The selected words were spoken by an adult male which was recorded using a unidirectional microphone (AHUJA AUD- 101XLR) into a Dell Inspiron 15 3000 series laptop (Realtek sound card) with Adobe Audition (version 3.0). The sampling frequency used was 44,100Hz. The recorded words were normalized to the same RMS amplitude.

   These words were assessed for the quality of sound and intelligibility. Five normally hearing, trained listeners were used for the purpose. The individuals listened to each word individually through Philips headphones in a quiet room at most comfortable level. They were required to rate the played sample on a scale of five (1-very poor, 2-poor, 3-satisfactory, 4-good and 5-very good). Only the samples which were rated as ‘very good’ were considered for use. Otherwise the words were recorded again to ensure good quality and intelligibility.

Following this the selected sample was assessed by 5 listeners to ensure that the words can be readily associated with the lexical category they belong to. The samples were played to the listeners using a set up similar to that used for the quality and intelligibility assessment. The four target lexical categories were assigned numbers as 1-fruits, 2-common objects, 3-animals and 4-professions and the listeners were required to listen to the words one by one, associate with the lexical category using the numbers assigned and same was noted down. Only the words that could be readily associated with the lexical category they belonged to by all the 5 listeners were used as the distractor stimuli. Appendix 1 shows the list of words used as MAD stimulus.

2) ***Non-meaningful Auditory Distractor (NMAD) Stimulus:*** In this the time-reversed version of the same 120 words that were used as MAD stimuli were used. The time reversal was done using Adobe Audition (version 3.0). The time reversed stimuli had same spectral and temporal characteristics as in MAD stimulus but were non-meaningful. Figure 3.2 shows a waveform representation of word ‘elephant’ and its time reversed form. The time reversed stimulus thus obtained was assessed by 5 listeners to ensure that they are not meaningful. All the 120 MAD stimuli when time-reversed were rated as non meaningful.

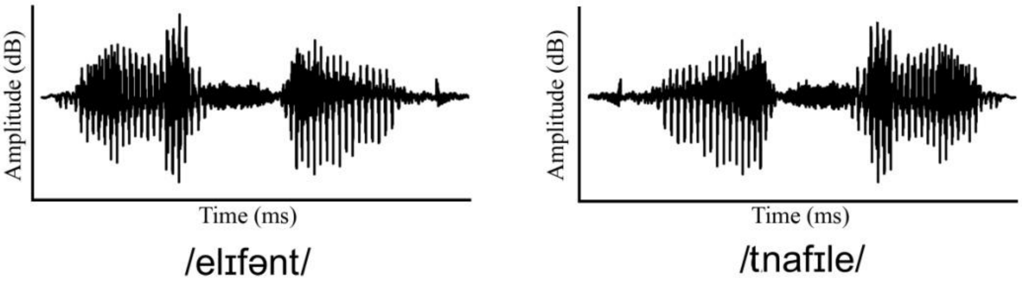

Figure 3.2: Representation of word ‘elephant’ (MAD stimulus) and its time reversed form (NMAD stimulus).

3) ***Visual Distractor (VD) Stimulus:*** The VD stimulus consisted of pictures representing the 120 MAD stimuli. These pictures were displayed against white background. The selected pictures were assessed by 5 individuals to ensure that they can be readily associated with the lexical category they belonged to. The selected pictures were displayed to the individuals using a Dell inspiron 15 3000 series laptop. The four targeted lexical categories were assigned numbers as 1-fruits, 2-common objects, 3-animals and 4-professions and the individuals were required to look at the pictures one by one, associate with the lexical category and write down assigned number for the perceived lexical category on the sheet provided. Only the pictures that could be readily associated with the lexical category they belonged to by all the 5 individuals were used as the visual distractor stimuli. Figure 3.3 shows an example of the pictures used as visual distractors under the lexical category fruits/vegetables (apple) and animals (dog).

Figure. 3.3: Example of VD in the lexical category fruits (apple) and animals (dog).

3.4 Test Environment

All the audiological tests were carried out in air conditioned, electrically shielded and sound treated rooms with ambient noise levels within permissible limits (ANSI S-3, 1991). The click and speech evoked ABRs were recorded in the Electrophysiology Lab, AIISH, Mysuru, which is air conditioned and electrically shielded. The ambient noise levels in the room were within 40dBSPL.

3.5 Test Procedure

The test procedure involved preliminary audiological evaluation and the actual experimental procedure. The preliminary audiological evaluations were only meant to ensure that participants selected in the present study satisfy all the selection criteria. The tests of preliminary audiological evaluation included pure tone audiomety, speech audiometry, immitance evaluation, oto-acoustic emissions, Screening Checklist for Auditory Processing in Adults (SCAP-A) and click evoked ABRs.

3.5.1 Preliminary Audiological Evaluation

Pure-tone Audiometry: Puretone thresholds were estimated using modified Hughson and Westlake procedure (Carhart & Jerger, 1959) at octave frequencies between 250 Hz and 8000 Hz in air conduction mode.

Speech Audiometry: Speech recognition threshold and word identification scores were obtained to rule out deficits in speech perception. Speech recognition threshold was obtained using the standard paired-word lists in Kannada (Rajashekar, 1978). The initial presentation level was 20 dBSL (ref: pure tone average) and subsequent reductions (10 dB steps) and increments (5 dB steps) were used to arrive at recognition threshold (ANSI S3.6- 1969). Word identification score was obtained at a fixed intensity of 40 dBSL (ref: speech recognition threshold) using the standardised phonemically balanced word list in Kannada (Yathiraj & Vijayalakshmi, 2005).

Immittance Audiometry: A 226 Hz probe tone at 85dBSPL was used to obtain the tympanograms by varying the air pressure in the ear canal from +200 to -400 daPa. Ipsilateral and contralateral acoustic reflex thresholds were measured for 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz using the same probe tone frequency.

Oto-acoustic Emissions: To check the integrity of the outer hair cell functioning transient evoked oto-acoustic emissions (TEOAEs) were obtained for 260 sweeps of nonlinear click stimuli at 80dBSPL. Signal to noise ratio (SNR) of more than 6 dBSPL in at least 3 consecutive octave frequencies, with reproducibility greater than 70% was considered as presence of OAEs. TEOAEs were tested in both the ears.

Screening Checklist for Auditory Processing in Adults (SCAP-A): All the participants were screened for auditory processing disorders using SCAP-A developed by Vaidyanath and Yathiraj (2014). It consisted of 12 questions and was scored on a 2-point rating scale. Participants who obtained more than 50% score (a score ≥6) were considered at risk for auditory processing deficits and were excluded from the study.

Click evoked ABRs: Click evoked ABRs were recorded using Biologic Navigator Pro EP system (Natus Medical Inc., Mundelein, USA) to test the integrity of neural pathway at the level of brainstem. Only if the results of click ABR were normal, the individual was considered for speech ABR recording. The stimulus and acquisition parameters used for recording click ABR are given in Table 3.1.

To ensure the reproducibility of the waveform, ABR was recorded twice from each ear using the above mentioned protocol. Only those individuals who had normal results in all the preliminary audiological tests served as participants for the actual experimental procedure.

Table 3.1: *Stimulus and acquisition parameters used for recording click evoked ABR*

Stimulus Parameters	
Stimulus type	Click
Repetition rate	11.1/sec
Polarity	Rarefaction
Click duration	100 µs
Intensity	80dBnHL
Transducer	ER-3A Insert earphone
Acquisition Parameters	
Analysis time	12ms
Filter setting	100Hz to 3000Hz
Electrode placement	Cz (+ve) M2 (-ve) M1 (Gnd)
Artefact rejection	31 µV
Amplification	1,00,000
No. of Sweeps	1500

3.5.2 Experimental Test Procedure

The speech ABRs were recorded in all the participants using ipsilateral single channel recording. The participants were seated on a reclining chair and were instructed to relax and minimize extraneous movements. The surface electrode sites wer cleaned before placing electrodes and inter-electrode impedance was maintained below 2 kΩ. The silver chloride disc electodes were placed in a vertical montage with Cz being positive, M2 being negative and M1 being the ground electrode sites,and the EEG was recorded. In all the participants, right ear was the test ear. The protocol used to record speech evoked ABR is given in Table 3.2.

Table 3.2: *Stimulus and acquisition parameters used for recording speech evoked ABR*

Stimulus Parameters	
Stimulus	Synthetic CV syllable- /da/ of 40ms
Repetition rate	10.9/s
Polarity	Alternating
Intensity	80dBnHL
Transducer	ER-3A Insert earphone
No. of Sweeps	3000/ recording
Acquisition Parameters	
Acquisition Window	-10ms to 70ms
Filter setting	100Hz to 3000Hz
Electrode placement	Cz (+ve) M2 (-ve) M1 (Gnd)
Artefact rejection	31 µV
Amplification	1,00,000

A Dell Inspiron 15 laptop with the audio output routed through a calibrated audiometer was used to present the MAD and NMAD stimuli to the left ear. The MAD and NMAD stimuli were presented at 40dBSL (ref:speech recognition threshld) through ER3A (Etymtotic Research. Inc) insert earphones. A numeric keypad with numbers from 1 to 4 was used to register the response of the participants in the distractor task.

The speech ABRs were recorded in four experimental conditions:

1. ***Baseline:*** In this, speech ABR was recorded without competing stimuli in the contralateral ear.
2. ***With meaningful auditory distractor:*** MAD stimuli were presented to the participant in the left ear in sets of four (3 from one lexical category and an odd ne from another lexical category). The participants were instructed to pay attention to the words that were being played and identify the odd one out. For the purpose of recording the responses of the odd one out task, after each set of MAD stimuli, the participants were required to indicate the position of odd item in the set by pressing the corresponding key on the keypad as shown in Figure 3.4(A). While the participant is listening to the MAD stimulus, speech ABRs were recorded. Participants had to obtain a minimum score of 80% in the identification task to ensure that they had attended to the distractor. The set up for stimulus delivery is shown in Figure 3.4(B).

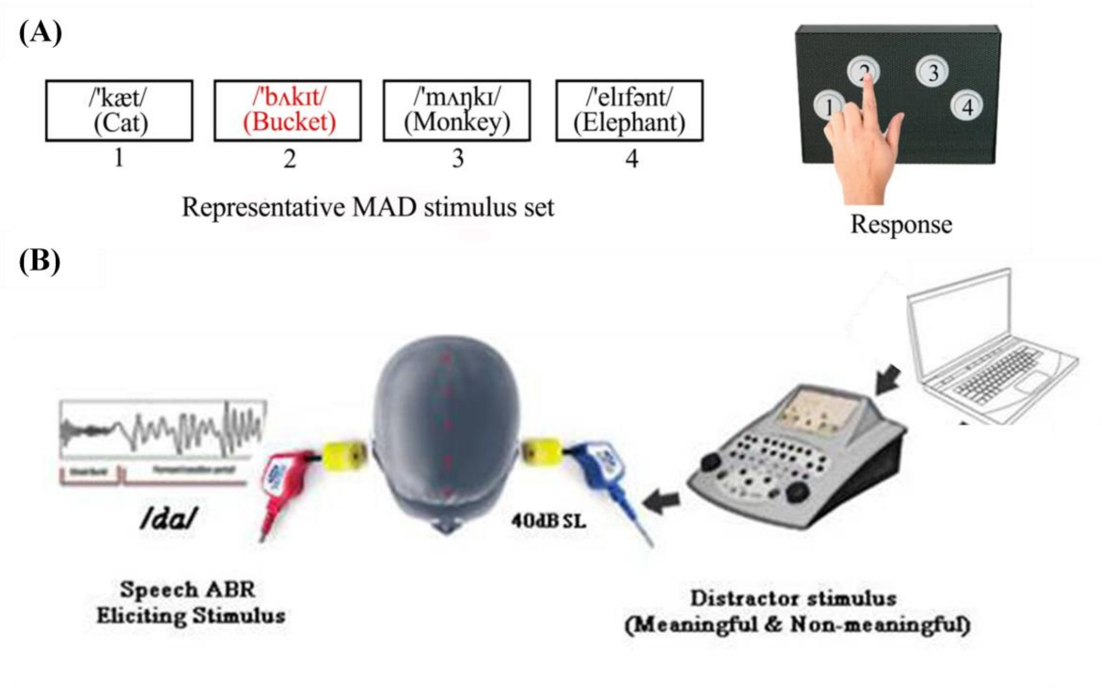

Figure. 3.4: Picture depicting a sample of stimulus set for MAD condition and its correct response (A) Schematic diagram depicting the stimulus delivery for Meaningful and Non-Meaningful Auditory Distractor conditions (B).

3. ***With non-meaningful auditory distractor:*** In this condition, the NMAD stimuli were played to the left ear in sets of four wherein there were 3 of same NMAD stimuli while one was a different NMAD stimulus. The participants were instructed to pay attention to the stimuli and identify the odd one. For the purpose of recording the responses of the odd one out task, after each set of NMAD stimuli, the participants were required to indicate the perceived position of odd NMAD in the set by pressing the corresponding key on the keypad as shown in Figure 3.5. While the participant is listening to the NMAD stimulus, speech ABRs were recorded. Participants had to obtain a minimum score of 80% in the identification task to ensure that they had attended to the distractor. The setup used for

stimulus delivery is similar to the setup used for NMAD condition (Figure 3.4B).

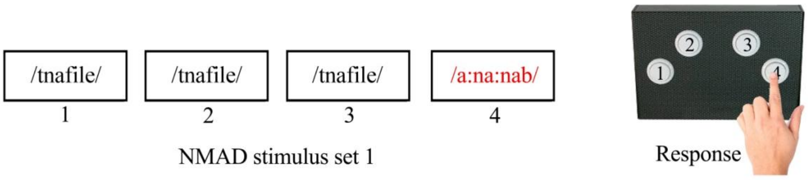

Figure 3.5: Picture depicting a representation of stimulus set for NMAD condition and the correct response**.**

4. ***With visual distractor:*** In this condition, speech ABR recordings were made while the participant attended to the visual distractor that was displayed on a laptop screen without audio playback. Set of 4 stimuli (3 from one lexical category and 1 from another) was displayed on the laptop screen against a white background and a ‘pick the odd one out’ task was given. For the purpose of recording the responses of the odd one out task, after each set of VD stimuli, the participants were required to indicate the position of odd picture in the set by pressing the corresponding key on the keypad as shown in Figure 3.6A. While the participant is attending to the VD stimulus, speech ABRs were recorded.

   Each VD stimulus was displayed on a laptop screen against white background for a duration of 60 seconds at the eyelevel, at 0º azimuth and a distance of 1 meter from the participant. Participants had to obtain a minimum score of 80% in the identification task to ensure that they had attended to the distractor. The set up used for stimulus delivery is shown in Figure 3.5B. While the participant is listening to the MAD stimulus, speech ABRs were recorded.

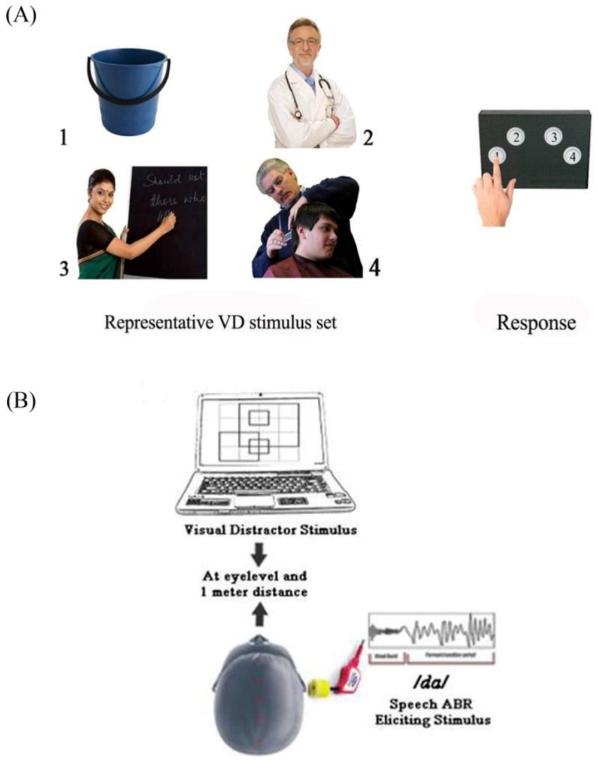

Figure 3.6: Picture depicting a sample of stimulus set for VD condition and the correct response (A) Schematic diagram depicting the stimulus delivery for visual distractor stimulus (B).

The order of the experimental conditions were randomized across participants to neutralize the order effect. To ensure the replicability of the speech ABRs in each condition, the responses were recorded twice in each condition.

3.6 Response Analysis

The recorded Speech ABR waveforms were analysed for the onset as well as the sustained portion (Frequency Following Response). Figure 3.7 shows the onset and sustained response of a speech ABR waveform elicited by syllable /da/ of 40ms.

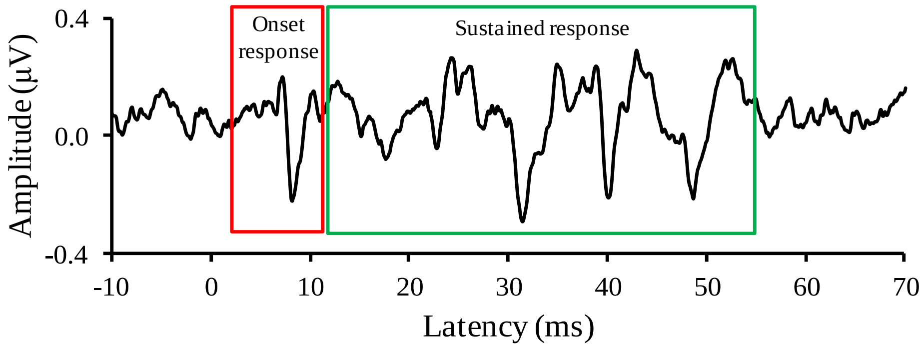

Figure 3.7: Onset and sustained response elicited by syllable /da/ of 40ms of a speech ABR.

3.6.1 Onset Response

The response elicited by the onset of the speech stimulus (/da/) comprised of a positive peak (wave V) which is followed by a negative trough. They were identified as transient peaks that occur within 6- 10ms after the stimulus onset (Skoe & Kraus, 2010a). The peak latency and peak to trough amplitude of wave V were noted down from each individual response. The slope of wave V was calculated by dividing peak to trough amplitude of wave V by its correspondidng duration.

3.6.2 Sustained Response

Sustained portion of the response was analyzed using fast fourier transform (FFT). The recorded responses were converted to a text file using AEP to ASCII converter (Natus Medical Inc., Mundelein, USA). The text files were imported into MATLAB R2010a and processed using a custom algorithm designed by Gnanateja (2013) (see Appendix 2). The Frequency following responses (FFRs) were windowed in the region of 11ms to 60ms using a tapered Hanning window to exclude the onset responses from interfering with the spectral components of FFR. The windowed waveforms were then zero padded to extend the duration to 1 second and the FFT was computed. In order to narrow down to the frequency region of F0, the /da/ stimulus output of the Biologic navigator PRO insert receiver was recorded using a Bruel and Kajer 2270 sound level meter running on C- weighted network. The spectrogram of the output was plotted and the F0 was estimated as 127Hz. The squared absolute value of the FFT was computed to obtain the spectral magnitudes of FFR. The spectral magnitudes at centre frequency of F0 (127Hz) and ten adjacent 1Hz bins on either sides along with the next 3 harmonics (H2, H3 & H4) were extracted from each individual waveforms. Further, spectra of the recorded responses in the four experimental conditions were extracted in the frequency range of 1 to 1000 Hz using a custom algorithm implemented in MATLAB R2010a.

3.7 Data Analysis

The amplitude and latency of onset responses and the spectral magnitudes at the F0 and the next three harmonics (H2, H3 & H4) in the four experimental conditions were analyzed using Statistical Package for Social Sciences (SPSS version 20). Initially the data in each condition was subjected to Shapiro-Wilik test of normality. The experimental conditions in which assumption of normality was assumed were subjected to one-way repeated measures ANOVA to check for the significant main effect of experimental condition on measures. Conditions in which assumption of normality was violated, non-parametric Friedman’s test followed by Wilcoxon signed rank test for pair-wise comparison was used.

The spectra of each of the participants in the four experimental conditions were imported to Cartool (Version 3.55) developed by Brunet (2014). A non parametric paired randomizations implemented in Cartool was used to compare the effect of experimental conditions on the spectral energy.

Chapter 4

RESULTS

The present study probed into the effect of auditory and visual distractors on the brainstem encoding of speech. Speech elicited auditory brainstem responses (ABR) was recorded in four conditions; without any distractor (baseline recording-BL), with meaningful auditory distractor (MAD), with non-meaningful auditory distractor (NMAD) and with visual distractor (VD).

The participants were required to have a minimum of 80% correct identification score while picking the odd one out in the three distractor conditions (MAD, NMAD & VD). The individual accuracy scores of the participants (N = 31) in the 3 experimental conditions are given in Appendix 3. All the participants qualified the minimum criteria and hence their ABR data was used for further statistical analysis. The brainstem responses were analysed for transient as well as the sustained portions. The transient responses were analyzed for the peak latency, peak to trough amplitude and the slope of wave V. The sustained portion was analyzed for the spectral magnitudes at the F0 region and the next three harmonics (H2, H3 and H4). Prior to subjecting the data for further analysis, outliers were identified in the primary data (N = 31) across all the measures and experimental conditions, and were subsequently removed (N = 11). The resultant data (N = 20) was checked for assumption of normality using Shapiro-Wilk test.

4.1. Results of Test of Normality

The results of the normality test indicated that, for transient portion, normality was assumed for peak latency, peak to trough amplitude and slope of wave V (df = 20, $p > 0.05$).

With regard to the sustained portion, the normality test results showed that normality has been assumed for all the harmonics in all conditions (df = 20, $p > 0.05$), except for amplitude of 4th harmonic in NMAD condition (df = 20, p = 0.01) and VD condition (df = 20, p = 0.00). In instances where the data was normally distributed, parametric test (repeated measures ANOVA) was used for statistically testing the effect of conditions. Whereas, if the data was not normally distributed, non parametric test (Friedman test) was used. The individual waveforms recorded in the four experimental conditions in the 20 participants of the study and their corresponding grand averages are shown in Figure 4.1.

4.2. Comparison of Onset Responses Across the Four Experimental Conditions

Latency, amplitude and slope of wave V were compared across the four experimental conditions (BL, MAD, NMAD & VD). The mean and standard deviation of the latency, amplitude and slope of wave V in the four experimental conditions are given in Table 4.1.

Comparison of the mean data across the four conditions showed that there were marginal differences across the four conditions in latency, peak to trough amplitude and slope of wave V. Wave V latencies were found to be higher for MAD and NMAD conditions compared to BL and VD conditions. Among BL and VD condition, BL had prolonged mean wave V latency compared to VD condition. The mean peak to trough wave V amplitude was highest for VD condition followed by MAD, BL and NMAD conditions. The mean data revealed that the wave V slope was highest in VD condition compared to BL condition and followed by MAD and NMAD condition.

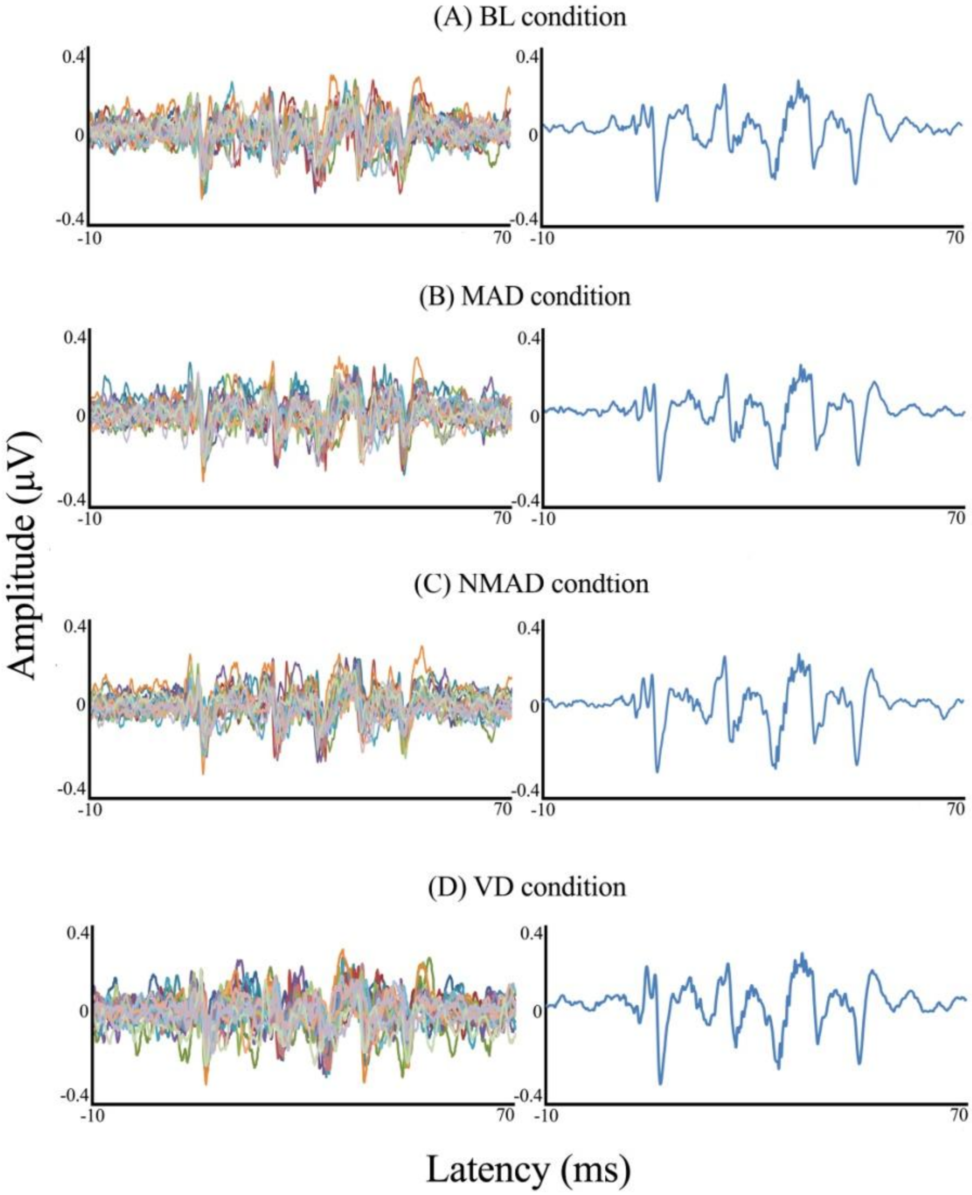

Figure 4.1: Individual waveforms [Left] recorded in the four experimental conditions [BL (A), MAD (B), NMAD (C) and VD (D)] and their corresponding grand average [Right] waveforms (N = 20).

Table 4.1: *Mean and standard deviation (in paranthesis) of the peak latencies of wave V in the four experimental conditions (N = 20)*

Experimental condition	Latency (ms)	Amplitude (μV)	Slope (μV/ms)
BL	6.432 (0.222)	0.359 (0.101)	0.391 (0.131)
MAD	6.470 (0.243)	0.361 (0.068)	0.389 (0.093)
NMAD	6.458 (0.237)	0.358 (0.076)	0.380 (0.115)
VD	6.424 (0.245)	0.369 (0.084)	0.397 (0.119)

Note: BL- Baseline, MAD- Meaningful auditory dictractor, NMAD- Non meaningful auditory distractor,VD- Visual distractor, SD- standard deviation.

Since the data was normality distributed in wave V latency, peak to trough amplitude and slope, repeated measures ANOVA was used to compare the main effect of conditions on the same. The results revealed that there is no main effect of condition on the latencies of wave V [F (1, 19) = 0.20, p = 0.65], peak to trough amplitudes of wave V [F (1, 19) = 0.37, p = 0.550] and slope of wave V [F (1, 19) = 0.06, p = 0.796].

4.3. Results of the Sustained Responses Across the Four Experimental Conditions

The spectral magnitudes at F0 centred at 127Hz and ten 1Hz bins around it along with the three subsequent harmonics (H2, H3 and H4) were extracted. Mean and standard deviation of the spectral magnitudes of the four harmonics (F0, H2, H3 and H4) in the four experimental conditions are given in Table 4.2.

Inspection of the mean data showed that there was no uniformity in the way mean spectral magnitude of the four harmonics varied across the four conditions. The mean spectral magnitude of F0 was same in BL and VD condition which was higher than that in MAD and NMAD conditions. Spectral magnitude of the second harmonic (H2) was highest in BL and VD conditions followed by MAD and NMAD conditions. Mean spectral magnitude of H3 did not differ across the four conditions. Whereas in H4, mean spectral magnitude compared to NMAD and VD conditions was higher in BL and MAD conditions.

Table 4.2: *Mean and standard deviation (in paranthesis) of the spectral magnitudes of the F0 and the 3 harmonics (H2, H3 & H4) in the four experimental conditions (N = 20)*

Experimental condition	Spectral harmonics			
	F0 (μV)	H2 (μV)	H3 (μV)	H4 (μV)
BL	0.058 (0.022)	0.021 (0.010)	0.008 (0.003)	0.008 (0.004)
MAD	0.054 (0.020)	0.020 (0.012)	0.008 (0.003)	0.008 (0.004)
NMAD	0.054 (0.016)	0.018 (0.010)	0.008 (0.002)	0.007 (0.003)
VD	0.058 (0.030)	0.021 (0.008)	0.008 (0.001)	0.007 (0.004)

Note: BL- Baseline, MAD- Meaningful auditory dictractor, NMAD- Non meaningful auditory distractor,VD- Visual distractor, SD- standard deviation.

A one-way repeated measures ANOVA was used to test the main effect of condition on the spectral magnitude at F0, H2 and H3. Results of repeated measure ANOVA revealed that there was no significant main effect of condition on the spectral magnitude of F0 [F (1, 19) = 0.00, p > 0.05], H2 [F (1, 19) = 0.22, p > 0.05] and H3 [F (1, 19) = 0.01, p > 0.05].

As the spectral magnitudes of H4 in the NMAD and VD conditions violated assumption of normality, Friedman's test was used to test the main effect of experimental condition on spectral magnitude of H4. The results of the Friedman's test revealed no significant main effect of condition on H4 amplitude [χ^2 (3) = 0.37, p = 0.945].

Furthermore, to test whether any difference exists beyond 10 bins adjacent to the 4 harmonics, the spectrum of the FFRs were extracted from the primary data (N = 31) in the entire range of frequencies from 1Hz to 1000 Hz region. It was then subjected to a non-parametric paired two tail-randomizations method implemented in Cartool software version 3.55 (By Denis Brunet, 2014) to test the significance of difference in spectral magnitudes across the four experimental conditions. Five thousand randomizations of the data were done to estimate the probability of existence of a difference across the conditions. The difference was considered significant if probability was less than 0.05. In this method, spectral information at each time point in a particular experimental condition is compared with spectral information in another experimental condition at the same time point. The results of the non-parametric paired two-tail randomizations are depicted in the Figures 4.2 to 4.7. In the figures, the area within the two consecutive green lines represent region of significant difference ($p < 0.05$) in the spectrum.

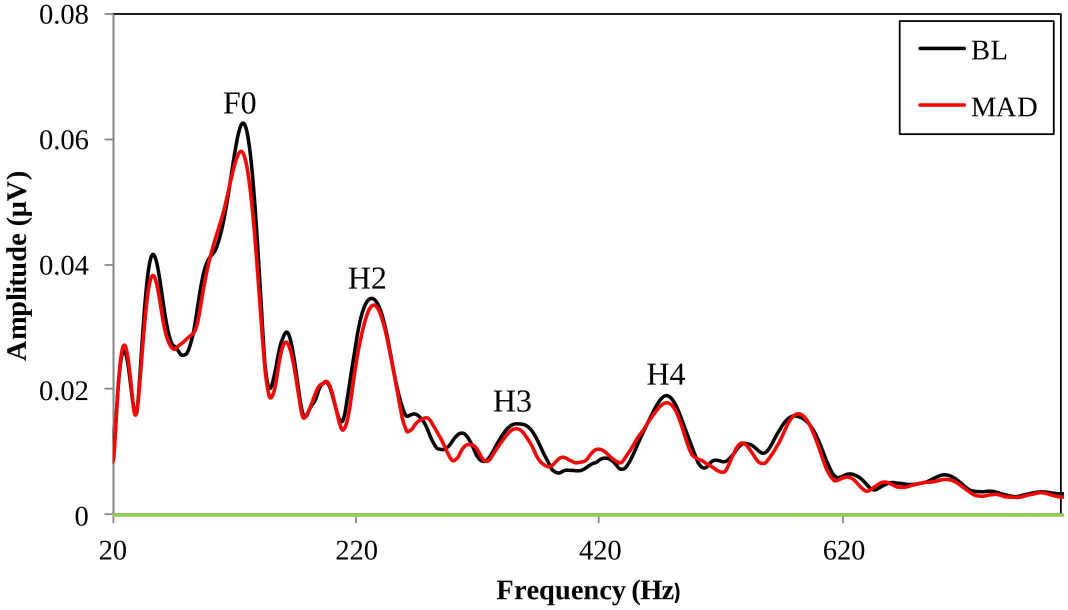

Figure 4.2: Comparison of mean spectra obtained in the BL and MAD conditions.

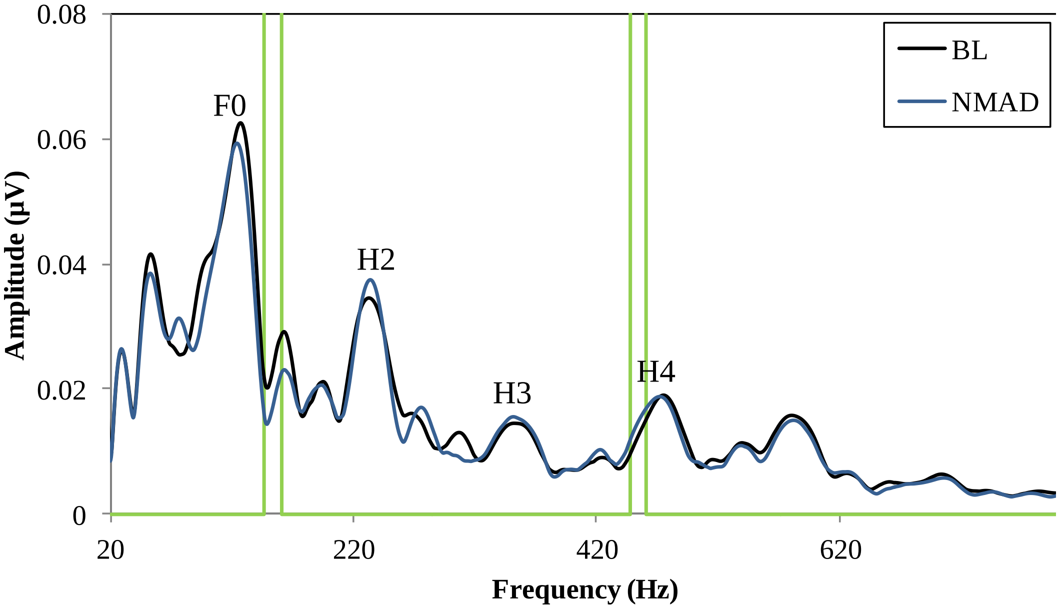

Figure 4.3: Comparison of mean spectra obtained in the BL and NMAD conditions.

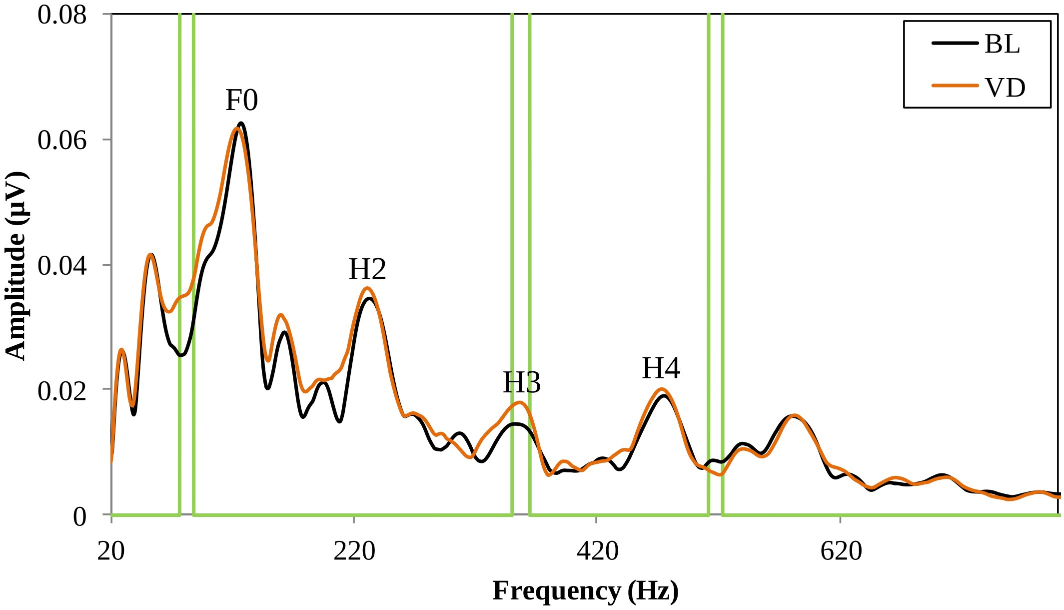

Figure 4.4: Comparison of mean spectra obtained in the BL and VD conditions.

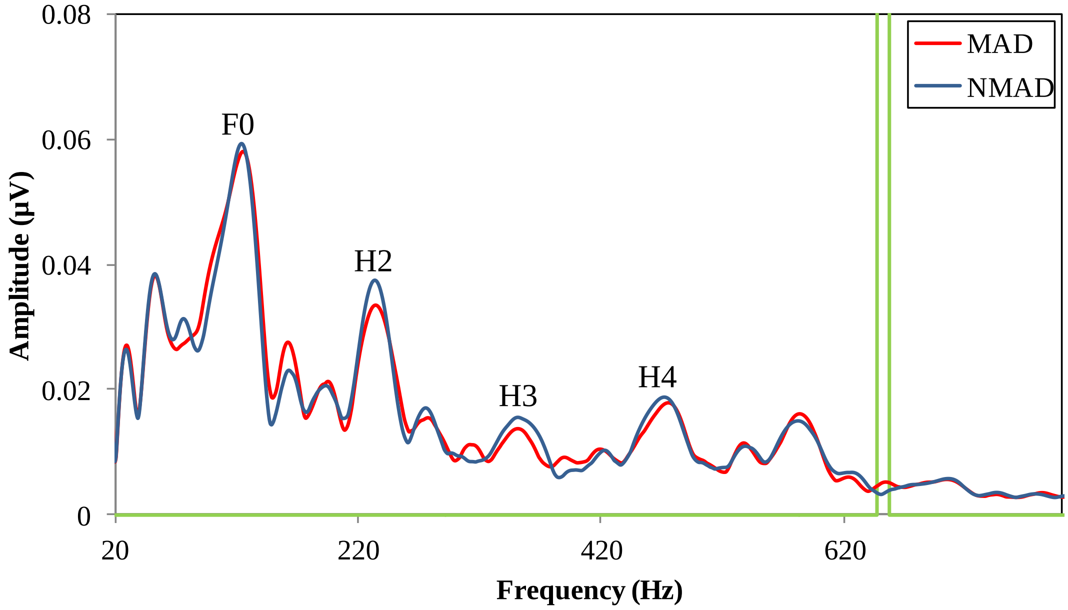

Figure 4.5: Comparison of mean spectra obtained in the MAD and NMAD conditions.

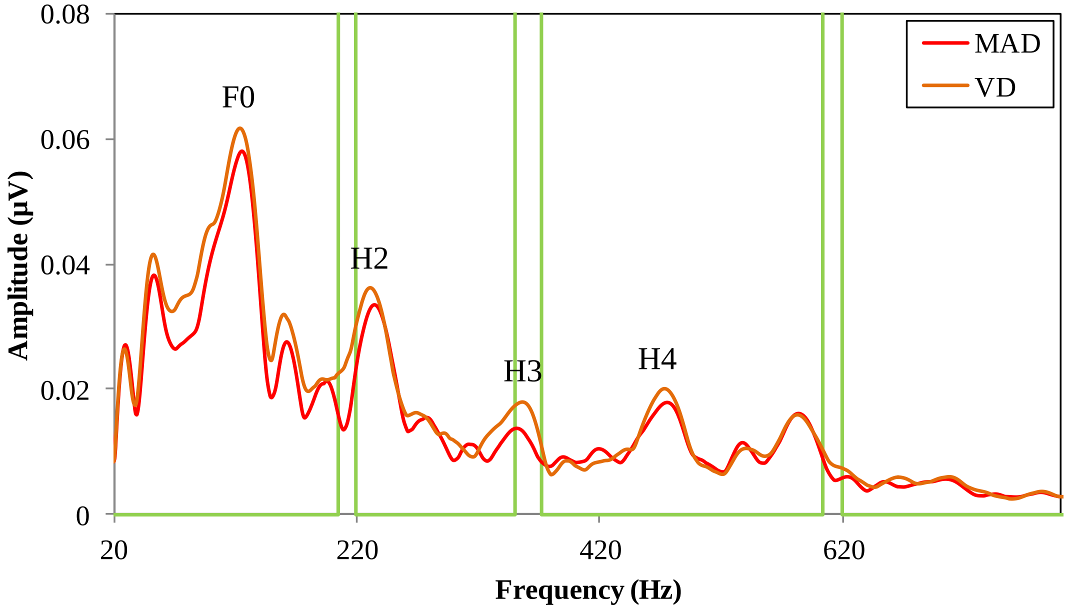

Figure 4.6: Comparison of mean spectra obtained in the MAD and VD conditions.

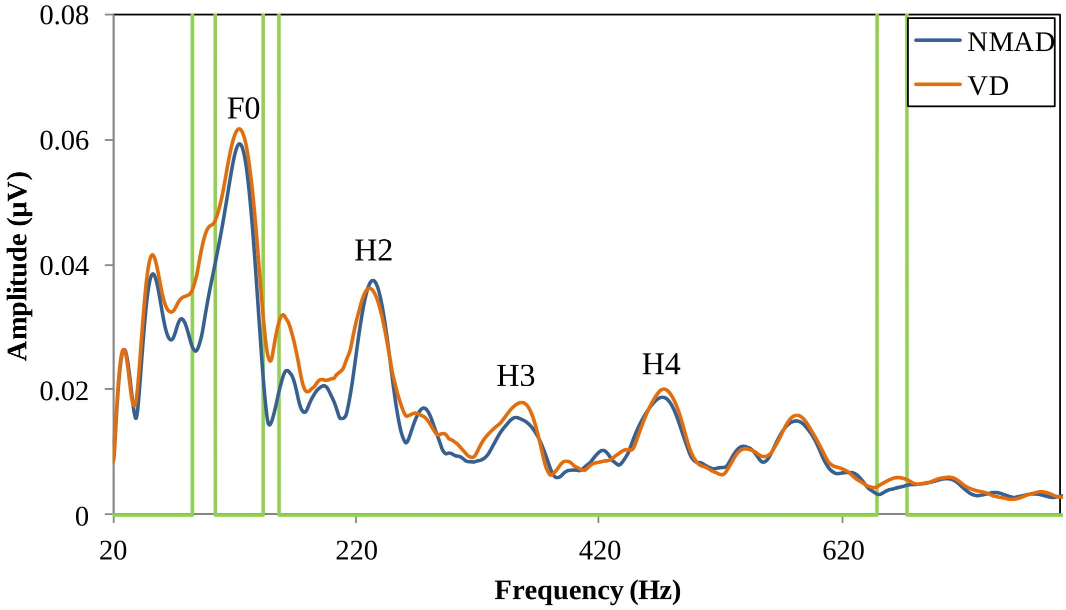

Figure 4.7: Comparison of mean spectra obtained in the NMAD and VD conditions.

The results of the non-parametric paired two-tail randomizations revealed that there was no significant difference between the spectrum obtained in BL and the MAD conditions ($p > 0.05$). On comparing the BL and NMAD condition, the results revealed that there is a significant difference ($p < 0.05$) in the spectrum from 145Hz to 160Hz (region adjacent to F0) and 447Hz to 460 Hz (region of H3). For the VD condition, it was observed that the overall spectral amplitudes were higher compared to the BL, MAD and NMAD conditions. Compared to the BL condition, spectral amplitudes in VD condition were significantly higher in the 76Hz to 87Hz (sub-harmonic region), 349-364Hz (region of H2) and 511Hz to 523Hz (region post H3) regions ($p < 0.05$).

Figure 4.6 reveals that the overall spectral magnitude in the MAD condition is slightly lower than the NMAD condition and this difference was not found to be statistically significant ($p > 0.05$). However, in the 646Hz to 657 Hz region, amplitude of the MAD spectrum was significantly higher than that in the NMAD condition ($p < 0.05$).

Similarly, comparison of the MAD and VD conditions (Figure 4.7) revealed that, the overall spectral magnitude in the VD condition is higher than MAD condition. This difference was statistically significant in the 204Hz to 218Hz (region adjacent to H2), 349Hz to 371Hz (region of H3) and 602Hz to 618Hz regions of the spectrum ($p < 0.05$).

The overall amplitude of spectrum in the VD condition was higher than the NMAD condition (Figure 4.8). The results revealed that statistically significant differences existed in the 84Hz to 103Hz, 142Hz to 155Hz (regions adjacent to F0) and 648Hz to 672Hz regions ($p < 0.05$).

Chapter 5

DISCUSSION

The purpose of the study was to investigate the effect of auditory and visual distractors on the onset and sustained brainstem responses elicited by a speech syllable. It was also of interest to compare the effect of meaningful and non-meaningful auditory distractors on the same. In the present study the meaningful auditory distractor (MAD) and non-meaningful auditory distractors (NMAD) were presented to the left ear while recording speech evoked auditory brainstem responses (ABRs) from the right ear. In the visual distractor (VD) condition, speech ABRs were recorded from right ear when participants attended to a VD stimuli. Overall, the results of the present study revealed no significant influence of distractors on the onset brainstem response. However significant influence was present on the sustained responses.

5.1 Influence of Distractors on Onset Brainstem Responses

The results revealed that there is no significant influence of distractors on the wave V latency, peak to trough amplitude and slope. Similar results have been reported earlier by Hillyard et al. (1973) and Gregory et al. (1989). They reported no significant effect of auditory and visual attention on the amplitude or latency of wave I-VI. Kuk and Abbas (1989) reported no effect of visual and auditory attention on the tone burst evoked ABR. However, Linden et al. (1987) and Papanicolaou et al. (1986) reported that wave V latency increased and amplitude reduced when participants performed a visual attention task and speech production task respectively. They attributed this finding to the attention induced efferent inhibition via the olivocochlear bundle which suppresses the irrelevent stream of neural activity.

The results of the present study can be explained in light of two possibilities. Firstly, there is no influence of the corticofugal pathways on the generators of wave V and hence the distractors did not affect the encoding of the stimulus onset at the level of brainstem. The second possibility is that, the distractor task that was used in the present study was not taxing enough to tap the effect. However, close observation of the mean data reveals higher wave V latencies in presence of distractor in the auditory domain when compared to baseline and visual distractor conditions. Furthermore, when the distractor in the auditory domain was meaningful, the prolongation in latency was higher than in non meaningful condition. Subtle differences between the conditions were also present for the wave V peak to trough amplitude and slope. Hence, its likely that corticofugal pathway influences the onset encoding. However, the effect of distractor conditions on onset responses was not statistically evident as the distractor task used in the present study might not be taxing enough to lead to a statistically significant effect.

5.2 Effect of Distractors on Sustained Brainstem Response

Decrease in frequency following responses (FFRs) in the presence of distractor indicates that the distractor stimulus in the opposite ear affects the temporal precision of the brainstem encoding of speech. The findings of the present study are in line with earlier reports regarding effect of attention on FFRs elicited by puretones (Galbraith & Arroyo, 1993; Galbraith & Doan, 1995; Hairston et al., 2013), missing fundamental stimuli (Galbraith & Doan, 1995), complex tonal stimuli (Galbraith et al., 2003) and vowels (Galbraith et al., 1998; Lehmann & Schönwiesner, 2014). All of them unequivocally reported an enhancement of response recorded from the attended channel and suppression of the unattended channel. Rinne et al. (2008) reported significant changes at the level of inferior colliculus when participants attended to an auditory task and they suggested the presence of top-down modulation mediated via the corticofugal pathways. Although the exact mechanism through which the stimulus in the opposite ear interferes with the brainstem encoding is not clear, the deviated attention could be playing a significant role. However, Galbraith and Kane (1993) and Varghese et al. (2015) reported no significant effect of attention on the FFRs and brainstem steady state responses respectively.

In the present study, compared to the baseline ABRs wherein no task was assigned, the brainstem encoding of the sustained portion was observed to be inhibited on the addition of a sensory driven task in the auditory domain. This finding may be attributed to (1) cortical influence on the brainstem processing via the corticofugal modulation or (2) contralateral suppression at the level of cochlea via the medial olivococlear bundle or (3) a combination of both. The corticofugal pathway functions as a link through which auditory cortical structures communicates with the sub-cortical structures. Based on the cortical processing load this might enhance or suppress the gain of sub-cortical structures, thereby making the subcortical processing a malleable phenomenon (Chandrasekaran et al., 2009; Skoe & Kraus, 2010b; Suga et al., 2000; Suga et al., 2002). At the peripheral level, the cochlear and neural potentials is influenced by activation of medial efferent neurons of the medial olivocochlear bundles (Galambos, 1956; Guinan & Gifford, 1988). The medial olivocochlear neurons synapse directly with the outer hair cells and hence the micromechanical properties of cochlea is altered via the efferent system (Terreros & Delano, 2015). Also, acoustic stimulation of the contralateral ear is known to reduce the amplitude of spontaneous rate of auditory nerve (Liberman, 1989). Therefore, it is possible that the auditory distractor used in the present study activated the medial olivocochlear neurons which inhibited the response at the level of cochlea and auditory nerve which in turn reflected as suppression in the FFR spectrum. Hence the inhibitory effect of auditory distractors on the brainstem encoding of speech is a cumulative effect of the corticofugal pathways and the contralateral suppression via the medial olivocochlear bundles. Isolation of the actual process that caused the inhibition from the above discussed possibilities is difficult from the present findings.

The spectral magnitude in the MAD condition was found to be slightly lower compared to the NMAD condition. The brainstem does not play a role in coding the meaning of a stimulus. Therefore the observed difference in the influence of distractors suggests the involvement of cortical structures in the brainstem encoding. In the presence of a meaningful distractor, the process of fine tuning of brainstem encoding through corticofugal pathway seems to be suppressed to a slightly greater extent.

Another important finding was the enhancement of spectral amplitude in visual distractor condition as compared to baseline and auditory distractor conditions. This suggests that the modulation of the brainstem responses is present even when the distractor is in another modality. Earlier report on effect of visual attention on FFRs by Hairston et al. (2013) revealed a contradictory finding. They reported that addition of a visual temporal discrimination task lead to reduction in spectral magnitude. In the present study the visual task used was lexical judgement task, and hence it is possible that whether the corticofugal influence is enhansive or suppressive in nature depends on the nature of the task. The cortical structures that are activated by a visual temporal discrimination task is different from areas activated for task involving visual lexical judgement (Dupont et al., 1993). Fidalgo, Conejo, González-Pardo and Arias (2014) reported that prefrontal and temporal cortices are activated for a visual temporal discrimination task. For a lexical judgement task in the form of a pick the odd one out paradigm, medial temporal lobe and the related visual areas are activated (Devlin & Price, 2007). Hence, it is plausible that this task-dependent differential cortical area activity regulates the corticofugal inluence differently. The finding that distractor in the auditory domain has a suppressive effect as opposed to enhancement seen on the addition of a visual distractor might also mean that the mechanisms of distractions are different across the different modalities. The distractor in the auditory domain seems to impose greater challenge for brainstem encoding.

5.3 Anatomical and Physiological Correlates

The results of the present study are suggestive of a top-down (corticofugal) phenomenon which is responsible for the spectral magnitude inhibition in the presence of a distractor in the auditory domain and spectral magnitude enhancement in the presence of a distractor in the visual domain. Though the present study cannot pinpoint to the neurophysiological source of the observed inhibition, the results can be better explained taking into consideration earlier reports of existence of a descending trisynaptic link between auditory cortex and peripheral auditory structures via inferior colliculus (Bajo et al., 2010; Suga et al., 2000; Terreros & Delano, 2015; Winer, 2006). The addition of an attentional task increases the load within the cortex. This results in activation of the corticofugal pathways which in turn inhibits or enhances the neuronal functioning at the level of brainstem. This influence exerted by the cortex on brainstem manifests as enhancement or suppression in the spectral magnitudes of FFR (Hairston et al., 2013). Furthermore, when a task is imposed in the same modality (as in addition of distractor in the auditory modality while recording the speech evoked ABR) the cortical load increases (Hairston et al., 2013; Nuñez & Malmierca, 2007; Rinne et al., 2008). Making judgements based on the meaning leads to further increase in the cortical load. The cortical neurons respond to this increase in cortical load by proportionate increment in the corticofugal inhibition. When the distractor is in a different domain (as in addition of distractor in the visual modality while recording speech evoked ABR), there is a shift in the cortical area activated by the distractor. Dupont et al. (1993) studied the brain areas activated for a visual identification and discrimination task using positron emission tomography and reported that, attending to a visual stimulus reorganizes the activity in the brain and decreases activity in brain regions other than the visual and related motor cortical areas. It is possible that, this task dependent shift in cortical area activation results in relatively less corticofugal inhibition compared to the auditory distractor condition or the baseline condition itself which manifests as a enhanced FFR. Hence it is safe to conclude that brainstem encoding of speech is not a passive functioning as understood with click evoked ABRs. There exists a continuous, online modulation of brainstem encoding by the auditory cortex via corticofugal pathways. Also, the semantic content of the distractor stimuli might be influencing the activation of the corticofugal regulation and in turn the brainstem encoding of speech. The semantic effect on the brainstem encoding of speech needs to be probed further with more taxing tasks.

Chapter 6

SUMMARY AND CONCLUSIONS

The focus of the present study was to test the effect of auditory and visual distractors on the brainstem encoding of speech. It was also of interest to test whether meaning of the auditory distractors has an effect on the brainstem encoding of speech.

Thirty one native speakers of Kannada in the age range of 18 to 24 years who had learnt English as their second language participated in the study. In each participant, auditory brainstem responses (ABRs) were recorded in the vertical montage for syllable /da/ in four stimulus conditions (a) Baseline without competing stimuli in the contralateral ear, (b) With meaningful auditory distractor (MAD) which consisted of 120 words selected from 4 lexical categories, (c) With non-meaningful auditory distractor (NMAD) which consisted of time reversed MAD stimuli, (d) With visual distractor (VD) which consisted of pictures representing the MAD stimulus. While the auditory distractors were presented through insert receivers at 40dBSL (ref: Speech recognition threshold), visual distractors were displayed on a laptop screen. A 'pick the odd-one' task was used to ensure attention towards the distractor.

The speech ABRs thus recorded were analysed for the transient as well as the sustained portion (Frequency following Response). The transient portion was analysed for the wave V latency, peak to trough amplitude and slope. The sustained portion was subjected to FFT for extracting the spectral magnitude of the F0 and the next three harmonics (H2, H3 & H4). FFRs were further analysed to derive spectra in the entire range of 1Hz to 1000Hz, from the individual recordings, in the four stimulus conditions. The resultant spectra in the four stimulus conditions were subjected to a non-parametric paired randomizations implemented in Cartool (version 3.55).

The results of the present study revealed that there is no significant effect of the four experimental conditions on the transient component of the speech evoked ABR. For the sustained responses, the results of the two-tailed randomizations revealed a significant effect of the four distractor conditions on the brainstem encoding of speech. It was observed that the overall spectral magnitude of the FFR in the auditory distractor conditions were lower than the baseline and visual distractor conditions. When the distractor was meaningful, the reduction in spectral magnitude was slightly larger than that in the non-meaningful condition. The overall spectral magnitude of the FFR in the visual distractor condition was higher compared to the baseline and the auditory distractor conditions.

Overall, findings of the present study imply that the brainstem encoding of speech is an active process. Attending to a distractor increases the cortical load which via the corticofugal pathways influences the brainstem encoding. When the distractor is in the same modality (as in auditory distractor while recording speech ABR), and when meaning is attached to the stimuli, the cortical load further increases and leads to comparatively higher suppression which reflects as a reduction in spectral amplitude. For distractor in another modality (as in visual distractor while recording speech ABR), the effect of the corticofugal pathway being enhancive or inhibitory depends on the task given. In the present study enhanced overall spectral amplitude on the addition of the visual distractor was observed. Hence it can be concluded that the attention driven corticofugal modulation can have either enhancive or inhibitory effect on the brainstem encoding of speech. The modality in which the distractor is given, type and difficulty of task have role in determining the magnitude of corticofugal modulation. Further, the results reveal that the semantic load of the distractor also has minor but true influence on the corticofugal activation. However this needs to be tested further.

From the results of the present study, it can be concluded that the brainstem processing of speech is a malleable phenomenon mediated online via the corticofugal pathways and is likely to be influenced by the modality and semantic content of the distractor.

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Appendix 1

Distractor Word List (120 Meaningful Auditory Distractor)

Sl. no	Animals	Common objects	Fruits & vegetables	Professions
1.	Elephant	Table	Apple	Policeman
2.	Goat	Chair	Orange	Cobbler
3.	Dog	Mirror	Grapes	Carpenter
4.	Lion	Fan	Banana	Fisherman
5.	Tiger	Television	Guava	Teacher
6.	Giraffe	Pen	Pineapple	Tailor
7.	Deer	Book	Watermelon	Painter
8.	Donkey	Bed	Cabbage	Driver
9.	Cat	Pillow	Papaya	Scientist
10.	Buffalo	Brush	Strawberry	Pilot
11.	Bear	Bottle	Onion	Postman
12.	Zebra	Cupboard	Coconut	Sportsman
13.	Camel	Umbrella	Lemon	Soldier
14.	Horse	Matchbox	Jackfruit	Farmer
15.	Crocodile	Pencil	Mango	Doctor
16.	Squirrel	Bucket	Pomegranate	Nurse
17.	Monkey	Comb	Ginger	Priest
18.	Leopard	Clock	Blueberry	Baker
19.	Cheetah	Plate	Cashew	Plumber
20.	Hippopotamus	Key	Almonds	Mechanic
21.	Snake	Needle	Pear	Dentist
22.	Sheep	Computer	Tomato	Accountant
23.	Rabbit	Window	Brinjal	Waiter
24.	Rhinoceros	Mobile	Potato	Engineer
25.	Fox	Refrigerator	Carrot	Magician
26.	Wolf	Ladder	Chilly	Singer
27.	Hyena	Thread	Beans	Barber
28.	Kangaroo	Paper	Pumpkin	Judge
29.	Tortoise	Cup	Cucumber	Fire fighter
30.	Lizard	Bag	Radish	Chef

Appendix 2

Algorithm implemented in MATLAB for FFT

(Reproduced with permission from Gnanateja. N (2013))

```
% The input file should be in a txt format and all the headers
should be
% removed. The file should only contain the waveform and no other
details
 %and should be placed in aseparate folder in the matlab directory.
%%
clear all;clc

epoch = 85.33; %the total epoch duration in milliseconds
prestim = 15;   % pre-stimulus time ignoring the negative sign
FFTstart = 11; %starting time range to run FFT
FFTend =60 ;  %ending time range to run FFT
outfile = 'vd20.xls';


fund = 127;
bin = 10;
%% Do not edit beyond this point
post = epoch -prestim; %post stimulus time
lowf0=fund-bin;  %F0 starting  frequncy
highf0=fund+bin; %F0 ending frequency

lowh2 = 2*fund - bin; %Second harmonic starting frequency
highh2 = 2*fund + bin; % Second harmonic ending frequency

lowh3 = 3*fund - bin; %H3 starting frequency
highh3 = 3*fund + bin; % H3 ending frequency

lowh4 = 4*fund - bin; %H4 starting frequency
highh4 = 4*fund + bin; %H4 ending frequency

[path]  =  uigetdir('C:\Users\Nike  Gnanateja\Documents\MATLAB\*.txt',
'select the folder with the ASCII files');
path = [path '\*.txt'];
files = dir(path);
nfiles = length(files);
randlist=1:1:nfiles;
files = char(files.name);
a = length(files);

FFTstart = FFTstart/1000;
FFTend = FFTend/1000;


%epoch details

for i= 1:nfiles
%number of points  and timescale
name = files(i,:);
a = dlmread(name);
n = length(a);
fs = n*1000/epoch;
time = -prestim/1000 :1/fs: post/1000 -1/fs;
zerotime = -prestim/1000:1/fs:0-1/fs ;

%baseline correction ref: prestimulus
detrend = a - mean(a(1:size(zerotime)));
```

```
%%spectral analysis%%

%Time slice%

[trash position1] = min(abs(time-FFTstart));
[trash position2] = min(abs(time-FFTend));

sample = (a(position1:position2))';

%zero padding%
lin = fs;
win = round(fs*(5/1000));
window = hann(win);
env = window(1:round((length(window))/2));
vne = fliplr(env');
sample(1:length(env)) = env'.*sample(1:length(env));
sample(length(sample)-length(vne)+1:length(sample))                    =
vne.*sample(length(sample)-length(vne)+1:length(sample));
zero = zeros(1,round(fs-length(sample)));
abc = [sample zero];



%FFT
spect = abs(fft(abc));

amp=spect.*(2./length(sample));
amp = amp(1:round(round(fs)/2));
n=length(spect);
freq=fs/n.*(1:n);

f=freq(1:(round(n/2)));

%%H1
fstartL =  find(f<=lowf0);
fstartL = fstartL(1,length(fstartL));
fstart = f(1,fstartL);
fendL = find(f>=highf0);
fendL = fendL(1,1);
fend = f(1,fendL);
range = f(fstartL:fendL);
f0 = amp(fstartL:fendL);
%find frequency with maximum amplitude

MAX = max(f0);
maxlocus = find(f0==MAX);

Fo = range(1,maxlocus);
H1 = mean(f0);

% H2
fstartL =  find(f<=lowh2);
fstartL = fstartL(1,length(fstartL));
fstart = f(1,fstartL);
fendL = find(f>=highh2);
fendL = fendL(1,1);
fend = f(1,fendL);
range = f(fstartL:fendL);
h2 = amp(fstartL:fendL);
H2 = mean(h2);

%H3
fstartL =  find(f<=lowh3);
fstartL = fstartL(1,length(fstartL));
```

```
fstart = f(1,fstartL);
fendL = find(f>=highh3);
fendL = fendL(1,1);
fend = f(1,fendL);
range = f(fstartL:fendL);
h3 = amp(fstartL:fendL);
H3 = mean(h3);
%H4
fstartL =  find(f<=lowh4);
fstartL = fstartL(1,length(fstartL));
fstart = f(1,fstartL);
fendL = find(f>=highh4);
fendL = fendL(1,1);
fend = f(1,fendL);
range = f(fstartL:fendL);
h4 = amp(fstartL:fendL);
H4 = mean(h4);

Head = {'subject' 'F0' 'F0Amp' 'H2amp' 'H3amp' 'H4amp'};
M = {name Fo H1 H2 H3 H4 };
header = Head;
analysis(i+1,:) = M;

end
analysis(1,:)=header;
xlswrite(outfile, analysis)

clear
```

Appendix 3

Individual accuracy scores in the distractor conditions (N= 31)

Participant No	Accuracy scores in the distractor conditions (%)		
	MAD	NMAD	VD
J1	93.75	94.11	100
J2	96.87	91.17	100
J3	100	85.29	98.48
J4	87.50	88.23	96.96
J5	96.87	88.23	100
J6	100	97.05	100
J7	100	94.11	96.96
J8	100	91.17	100
J9	100	88.23	100
J10	93.75	88.23	93.93
J11	90.62	97.05	100
J12	84.37	88.23	100
J13	100	91.17	100
J14	100	94.11	100
J15	100	94.11	100
J16	96.87	100	95.45
J17	100	97.05	100
J18	93.75	91.17	93.93
J19	100	85.29	98.48
J20	96.87	82.35	98.48
J21	93.75	91.17	100
J22	100	82.35	96.96
J23	100	97.05	100
J24	90.62	91.17	100
J25	87.5	85.29	100
J26	100	82.35	100
J27	96.87	91.17	100
J28	100	88.23	90.90
J29	96.87	82.35	100
J30	96.87	88.23	98.48
J31	90.62	97.05	100