# CORTICAL AUDITORY EVOKED POTENTIAL ASSESSMENT ON PASSIVE SPEECH PERCEPTION USING CONTRAST OF VOICING AND ARTICULATION PLACING AMONG SUBJECTS WITH SENSORINEURAL HEARING LOSS

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## ABSTRACT

Hearing ability is one major requirement for human to communicate through language and speech for social interactions. Despite the availability and usage of high technological hearing aid devices, individuals with sensorineural hearing loss (SNHL) reported dissatisfaction. Such displeasures were reported mostly due to intelligibility disruption to the desired signal perception especially in the noisy circumstances, which in turn contribute to device abandonment. The deficiency in the human auditory system on individuals suffering from SNHL is known to be associated with the difficulty in detection of various speech phonologic features that are frequently related to speech perception. In our present development, we evaluate the neurological changes in speech perception difficulties from normal as well people with sensorineural hearing deficit. The main goal of the study is to investigate the impact of speech articulation in place (/ba/ versus /da/) against voicing (/ba/ versus /pa/) contrast using Malay consonant-vowel (CV) speech stimulus towards cortical auditory evoked potential (CAEP) between healthy normal hearing and those suffering from SNHL. CAEPs were tested on 12 right-handed Malaysian male adult subjects (native Malay speakers) having bilateral SNHL and 12 healthy right-handed Malaysian male subjects (native Malay speakers) served as a control group. All volunteers were presented with two sets of Malay CV auditory speech stimuli (/ba/ versus /da/ and /ba/ versus /pa/) delivered at 80 dB sound pressure level (SPL) in an oddball passive paradigm. The two-way repeated measure ANOVAs showed no significant differences in the average CAEP amplitudes and latencies of the responses elicited by the standard and deviant stimuli. P3 was the most detectable CAEPs components appeared significantly in both responses followed by N2, N1, P2 and finally P1. The finding revealed the pattern of CAEPs response recorded at higher activation and longer latency when stimulated by voicing contrast cues compared to position contrast.

Interestingly, SNHL population elicited greater amplitude with prolonged latencies in the majority of the CAEP components in both speech stimuli. The MMN responses elicited by the SNHL patient were almost half smaller and recorded at longer latencies on both CVs speech stimuli in comparison with that in controls. The assessment of response strength (amplitudes) and response timing (latencies) for the CAEPs indicate the functionality of human brain which may have different processing capabilities depending on the phonological structure of the speech itself and discriminant processing capacity. The existence of different frequency spectral and time-varying acoustic cues of the speech stimuli reflected by the CAEPs response strength and timing recommend that the brain may have an easier task processing in the position contrast compared to voicing stimuli. This finding indirectly provide insight towards CAEP understanding in evaluating passive speech perception of human auditory process to convey better rehabilitation program in the future especially on the difficult to test scenario.

# ABSTRAK

Keupayaan pendengaran adalah satu keperluan utama bagi manusia untuk berkomunikasi melalui bahasa dan pertuturan untuk interaksi sosial. Walaupun kebolehan mendapat dan menggunakan peranti bantuan pendengaran teknologi tinggi, individu yang mempunyai kehilangan pendengaran sensorineural (SNHL) melaporkan rasa tidak puas hati seperti dilaporkan kebanyakannya disebabkan oleh kejelasan gangguan kepada persepsi isyarat yang dikehendaki terutama dalam hal keadaan yang bising, yang seterusnya menyumbang kepada peranti ditinggalkan. Kekurangan dalam sistem pendengaran manusia pada individu yang mengalami kehilangan pendengaran sensorineural (SNHL) yang diketahui berkaitan dengan kesukaran untuk mengesan pelbagai ciri ucapan fonologi yang sering berkaitan dengan persepsi pertuturan. Dalam perkembangan zaman sekarang ini, kita menilai perubahan neurologi dalam ucapan kesukaran persepsi dari biasa dan juga orang-orang dengan defisit pendengaran sensorineural. Matlamat utama kajian ini adalah untuk menyiasat kesan artikulasi ucapan di tempat (/ba/ melawan /da/) terhadap menyuarakan (/ba/ melawan /pa/) Sebaliknya menggunakan konsonan-vokal (CV) rangsangan ucapan Melayu antara yang sihat pendengaran dan mereka yang mengalami SNHL. CAEPs telah diuji ke atas 12 subjek tangan kanan Malaysia lelaki dewasa (bertutur bahasa Melayu asli) yang mempunyai SNHL dua hala dan 12 subjek lelaki Malaysia tangan kanan sihat (bertutur bahasa Melayu asli) berkhidmat sebagai kumpulan kawalan. Semua sukarelawan telah dibentangkan dengan dua set konsonan-vokal rangsangan ucapan auditori Malay (/ba/ melawan /da/ dan /ba/ melawan /pa/) diserahkan di 80 dB tahap tekanan bunyi (SPL) dalam paradigma oddball pasif. Kedua-dua hala berulang langkah ANOVAs menunjukkan tiada perbezaan yang signifikan dalam purata amplitud CAEP dan latencies daripada jawapan mencungkil oleh rangsangan standard dan sesat. P3 adalah CAEPs yang paling dikesan komponen muncul dengan ketara dalam kedua-dua tindak balas diikuti oleh N2, N1, P2 dan akhirnya

P1. Dapatan kajian menunjukkan corak sambutan CAEPs direkodkan pada pengaktifan yang lebih tinggi dan kependaman lagi apabila dirangsang dengan menyuarakan isyarat berbeza berbanding kedudukan kontras. Menariknya, sensorineural kehilangan pendengaran penduduk mencungkil amplitud lebih besar dengan latencies berpanjangan dalam kebanyakan komponen CAEP dalam kedua-dua rangsangan bersuara. Maklum balas MMN mencungkil oleh pesakit SNHL yang hampir separuh lebih kecil dan direkodkan pada latencies lagi di kedua-dua Kurikulum Vitae rangsangan ucapan berbanding dengan yang di dalam kawalan. Pengukuran kekuatan balas (amplitud) dan masa tindak balas (latencies) bagi CAEPs menunjukkan bahawa otak boleh mempunyai keupayaan pemprosesan yang berbeza bergantung kepada struktur fonologi bersuara itu sendiri dan kapasiti pemprosesan diskriminan. Kewujudan spektrum frekuensi yang berbeza dan masa yang berbeza-beza isyarat akustik rangsangan ucapan yang dicerminkan oleh kekuatan tindak balas CAEPs dan masa menunjukkan bahawa otak boleh mempunyai pemprosesan tugas yang lebih mudah berbanding kedudukan berbanding rangsangan menyuarakan. Dapatan ini secara tidak langsung memberikan wawasan ke arah CAEP pemahaman dalam menilai persepsi ucapan pasif proses pendengaran manusia untuk menyampaikan program pemulihan yang lebih baik pada masa akan datang terutama pada sukar untuk senario ujian.

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## LIST OF SYMBOLS AND ABBREVIATIONS

| | | |
|---|---|---|
| % | : | Percentage |
| µV | : | Microvolt |
| ABR | : | Auditory Brainstem Response |
| Ag/AgCl | : | Silver/Silver Chloride |
| ANOVA | : | Analysis of Variance |
| C | : | Central |
| CAEP | : | Cortical auditory evoked potential |
| CMS | : | Common mode sense |
| CV | : | Consonant-vowel |
| d’ | : | D prime |
| dB | : | Decibel |
| df | : | Degree of freedom |
| DOSH | : | Department of Occupational Safety and Health |
| DRL | : | Driven right leg |
| EEG | : | Electroencephalogram |
| EMD | : | Empirical mode decomposition |
| ENT | : | Otorhinolaryngology |
| EP | : | Evoked potential |
| ERP | : | Event-related potential |
| F | : | Frontal |
| F | : | Formant |
| fMRI | : | Functional Magnetic Resonance Imaging |
| HL | : | Hearing level |
| Hz | : | Hertz |

| | | |
|---|---|---|
| ISI | : | Inter-stimulus interval |
| K | : | Kilo |
| MATLAB | : | Matrix laboratory |
| MEG | : | Magnetoencephalography |
| MMN | : | Mismatch Negativity |
| MMSE | : | Mini-Mental State Examination |
| ms | : | Millisecond |
| N1 | : | Negative deflection at 100 ms (N100) |
| N2 | : | Negative deflection at 200 ms (N200) |
| NH | : | Normal hearing |
| P | : | Parietal |
| *P* | : | *P* value |
| P1 | : | Positive deflection at 100 ms (P100) |
| P2 | : | Positive deflection at 200 ms (P200) |
| P3 | : | Positive deflection at 300 ms (P300) |
| PTA | : | Pure tone audiometry |
| RT | : | Reaction time |
| SD | : | Standard deviation |
| SEP | : | Somatosensory evoked potential |
| SNHL | : | Sensorineural hearing loss |
| SNR | : | Signal to noise |
| SPD | : | Sensory processing disorders |
| SPL | : | Sound pressure level |
| SPSS | : | Statistical Package for the Social Sciences |
| STG | : | Superior temporal gyrus |
| STS | : | Superior temporal sulcus |

| | | |
|---|---|---|
| T | : | Temporal |
| UMMC | : | University Malaya Medical Center |
| V | : | Volt |
| VEP | : | Visual evoked potential |
| VERP | : | Visual event-related potential |
| VOT | : | Voice onset time |
| Α | : | Alpha |
| Β | : | Beta |
| Γ | : | Gamma |
| Δ | : | Delta |
| Θ | : | Theta |

## LIST OF APPENDICES

# CHAPTER 1: INTRODUCTION

## 1.1 Background

Hearing loss is mainly caused by a gradual malfunction of the brain auditory process in response to sound stimuli. Exposure to noise, presbycusis (aging), autoimmune inner ear disease and traumatic injury have been recognized as main reasons for contributing hearing impairment. On the awareness of these issues, worldwide was expected to bring the healthcare hearing rehabilitation to its level best. A hasty look at the statistics reveals the increasing number of hearing loss patients, especially in the elderly population. In Malaysia, it is predicted that in 2020, the elderly population is expected to reach 3.9 million people and contribute to 11.3% of the total Malaysian population (Rosdina et al., 2010, 2012). The statistics investigation revealed an increment about 215% of hearing problems reported from 2010 to 2014 and the scenario was even worse compared to other diseases (Department of Occupational Safety and Health (DOSH) Ministry of Human Resources, 2015). Noise-induced hearing loss is recognized as the major typical occupational disease experienced by workers (78.1%) as compared with other diseases (Department of Occupational Safety and Health (DOSH) Ministry of Human Resources, 2015). Figure 1.1 illustrated the statistic based on the occupational disease and poisoning received and investigated in 2014.

Evaluation of type, degree and configuration of hearing loss could be measured using pure tone audiometry (PTA) test, auditory brainstem response (ABR) and cortical auditory evoked potential (CAEP) analysis. Commonly, PTA test was performed to determine the hearing sensitivity level and this test involves both peripheral and central auditory systems. The result will be represented in the form of graph displaying intensity as a function of frequency so-called audiogram.

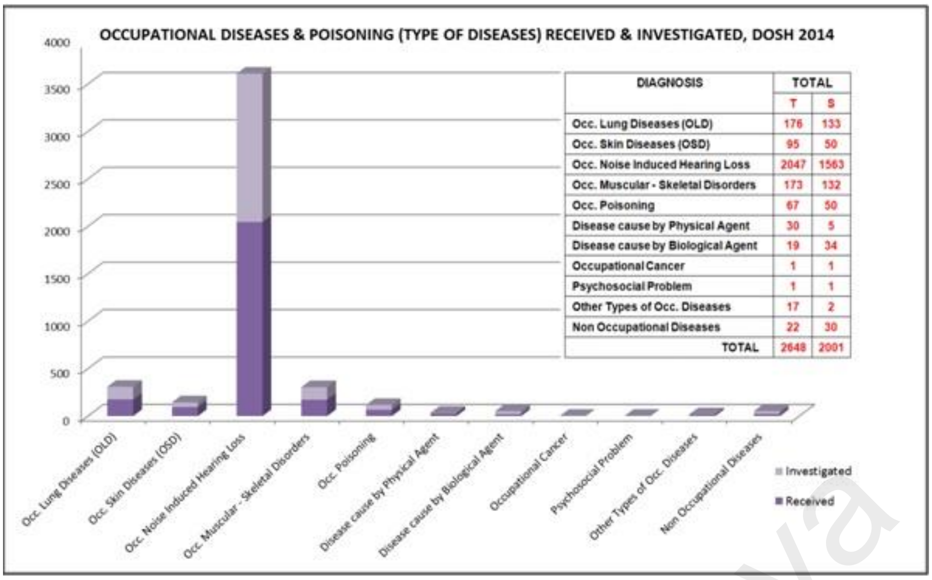


Figure 1.1: Occupational disease and poisoning received and investigated for the year 2014 (Department of Occupational Safety and Health (DOSH) Ministry of Human Resources, 2015).

Intensity is defined as the level of sound power measured in decibels while loudness is the perceptual correlate of intensity (Cook, Music, & Sound, 1999; Ladefoged & Maddieson, 1998). Determination of different types of hearing loss was done using Rinne and Weber tests. Both these evaluations involving interpretation of auditory mechanism response on air conduction and bone conduction.

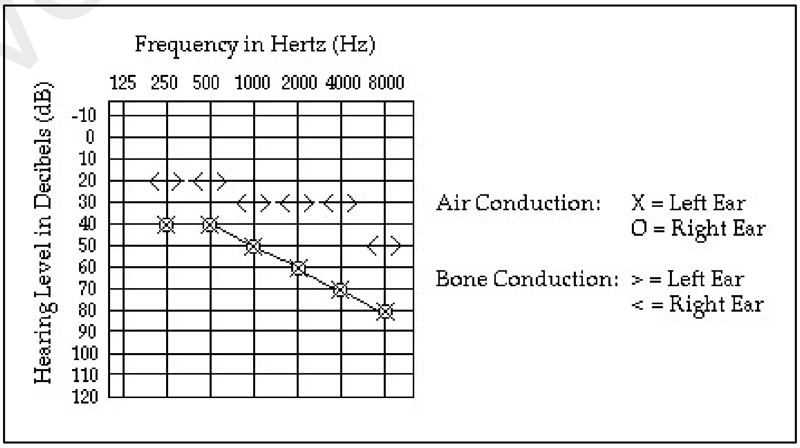


Figure 1.2: Pure tone audiogram (Association, 2005).

An air conduction test involving sensitivity assessment when the signal is transferred through the outer, middle and inner region and through the brain cortex. Compared to bone conduction technique, the stimulus is transferred through the bones of the skull to the cochlea and then through the auditory pathways of the brain. This technique bypassing the outer and middle region of the ear as to evaluate nerve-related hearing loss. Auditory brainstem response (ABR) is a neurological test of auditory brainstem function in response to auditory stimuli which is usually associated with evoked potential response. It commonly involves a click stimulus that produces a response from the hair cells of the cochlea, the signal travels along the auditory pathway from the cochlear nuclear complex to the inferior colliculus in midbrain generates wave I to wave V.

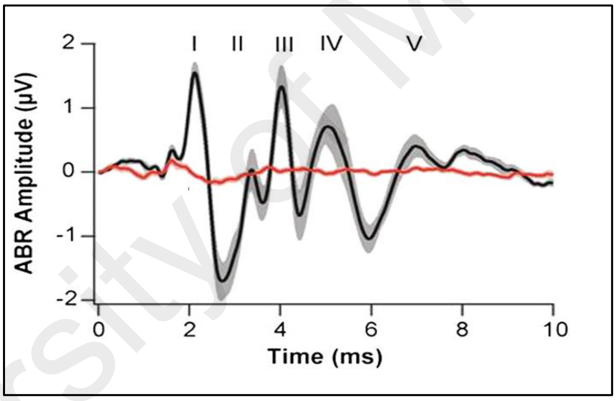


Figure 1.3: A typical auditory brainstem response (ABR) from an adult with normal auditory function (Bidelman, 2015).

CAEP is a non-invasive technique used by the audiologist and clinicians to be used as one of the diagnostic tools in providing objective information on the maturation of the human auditory system. Generally, CAEP was used in the children, infants and difficult to test patient since this test do not require subject's concentration. The behavioral analysis of this psychoacoustic detection of speech sound still lagged behind and remains unclear despite several decades of research. Thus, our present study emphasized the significance of CAEP on performing discriminant tasks between distinct speech sound properties as to impart better knowledge in understanding CAEP neuronal activation of

SNHL. Early hearing treatment would be beneficial for those suffering from SNHL as the fact that it could help to lessen the severity over time which literally able to transform their lives. Hearing aids, consultation, aural rehabilitation and implants are several options that might assist hearing impaired patient towards better hearing function.

Aforementioned, hearing aids and cochlear implants are the foremost elements in the rehabilitation process of SNHL population. Advancement of these assistive devices has evolved drastically in the recent decades to a level of transition in life communication. Nowadays, hearing aid devices promising unique user-friendly technology and advanced features to cope with the surrounding background noise using digital programming technology. However, even with key advances in hearing devices and implants, numerous sensorineural hearing impaired patients remain reluctant to use hearing aid devices and reported dissatisfaction with the device performance especially on capturing and recognizing the desired speech signal. This phenomenon leads to vast interest in understanding the main factors contributed to these abandonments. Previous investigators propose of some disruption experienced by SNHL population in discriminating various acoustical properties and phonological features in the speech sound (Anderson, Parbery-Clark, White-Schwoch, Drehobl, & Kraus, 2013; Korczak & Stapells, 2010; Oates, Kurtzberg, & Stapells, 2002b; Tavabi, Elling, Dobel, Pantev, & Zwitserlood, 2009). Hearing rehabilitation primarily aimed at reinstating effective hearing capability as near normal manner as possible. Achieving this goal requires well-designed assistive hearing devices that able to fulfill and surpass user expectation. Therefore, the present study concentrating on the conceptual understanding of how the neuronal representation of the human auditory mechanism involving nerve-related hearing loss population would be beneficial in overcoming current devices drawbacks, which in turn, provide insight in higher user satisfaction.

## 1.2 Problem statement

Initially, researchers and clinicians could not able to understand the main reason contributing to patient's displeasure even with the best suitable chosen assistive device and tend to foster interest in understanding the brain mechanism in discriminating speech phonologic features. Accurate speech perception within features of speech articulation through spoken language is essential for human to communicate during social interactions. The speech acoustic phonologic features such as voice/voiceless distinction, place, and manner of articulation provide a crucial complexity mapping mechanism which creates a stable neuronal representation in the human auditory system. To date, degraded speech perception among people with SNHL are still remaining unclear and there are still remaining an apparent gap between the device and SNHL population in terms of restoring missing functions. A number of studies done so far declared how the neurophysiological index happened between a native and non-native speaker in terms of modulated phoneme speech perception (Aaltonen et al., 2008; Bien, Hanulikova, Weber, & Zwitserlood, 2016; Shi & Lu, 2009). Taken together, its discovery indirectly resurrects vast interest within the same line of field especially on the CAEP variation in terms of discriminating speech perception between native and non-native speaker. Due to insufficient number of evidence regarding the use of CAEP as a tool for Malaysian population, the present endeavor helps to point out on the neurophysiological manifestation to its relationship to language memory trace for Malaysian reference, in part, with a limitation of ethic variation (only involved Malaysian Malay population).

Thus, to clarify these controversial findings, this research study focused on the measurements of CAEPs response strength (amplitude) and timing window (latency) which could provide an objective information with reference to auditory processing, that underlie speech perception in normal as well as in difficult-to-test patients (e.g., infants, children, and difficult-to-test patients). The study is to investigate if CAEP components show different pattern in response latencies and amplitudes between speech stimuli which are differ in terms of their articulation features (i.e. placing contrast vs voicing contrast) between healthy subjects with SNHL population towards Malaysian Malay population. Development of such electrophysiological measures can provide audiologist and clinicians with plausible knowledge regarding the potential benefits that hearing rehabilitation implement at various levels of cognitive processing involved in auditory perception, at the same time suggest new methods for difficult to cooperate patients in evaluating speech perception testing. We hope that the CAEPs responses will provide an effort towards understanding how the brain processes various features of speech articulation in SNHL people during passive speech perception so as to convey better rehabilitation program in the future. This is crucial in providing their ability to understand speech and compensating with daily listening environment.

## 1.3 Purpose of the study

The objectives of the study are:

1. To investigate the effects of cortical auditory evoked potential components (P1, N1, P2, N2, MMN and P3) as a measure of voice/voiceless distinction against place of articulation involving consonant-vowel stimuli during passive listening between healthy normal and individuals suffering from SNHL.
2. To identify the presentation of MMN as it appears in response to Malay CV stimuli to disclose any neuropathological changes.

An attempt was made in this CAEPs study to effectively distinguish between distinct speech articulations properties of the Malaysian Malay native speaker's having hearing loss.

## 1.4 Significance of the study

This research study creates more beneficial direction on the significance of CAEP components in discriminating various speech of articulation for clinicians in specific populations especially in difficult-to-cooperate clinical population (e.g., infants, children, and difficult-to-test patients) in which behavioral measures are hard to obtain. As a first contribution of this dissertation, we compare the CAEPs responses between healthy normal and people suffering from SNHL. There is no study done in evaluating passive neuronal activation involving SNHL population during discrimination of placing and voicing features of speech stimuli. It could give us a unique window to look into the perception benefits of speech that SNHL patients derived from which leads to hearing aids abandonments. In addition, the present investigation highlighted on the CAEP data for Malaysian population since no such study available for evaluating speech perception among Malaysian clinical population. Therefore, these electrophysiological measures can equip audiologist and clinicians with useful knowledge concerning the potential deprivation experience by hearing impaired individuals in auditory perception besides determined what type of speech stimuli that might be useful in measuring speech perception abilities especially in Malay Malaysian ethic group.

## 1.5 Scope of the study

The current study involves Malaysian Malay male adults between 20 – 45 years of age for both normal hearing and sensorineural impaired volunteers. The study uses the wireless Enobio electroencephalogram (EEG) device for data collection and MATLAB

R2013a program for device connection and data interpretation and analysis. This study limited to mild and moderate levels of hearing loss only.

### 1.6 Organization of the dissertation

This research exploited the area of CAEP on hearing impaired individual while performing the discriminant task. **Chapter 1** gives a concise overview of the background of the study, problem address in this research and the objectives are presented, followed by scope limitation of the study.

**Chapter 2** of this dissertation presents the detailed literature reviews of previous research regarding the CAEP investigations. This chapter includes several subtopics to enhance holistic approach towards related work. In this review of the literature, the significant and controversial issues regarding the CAEP's methods of evaluation were critically discussed and compared.

**Chapter 3** covers the experimental design and methodology used for the entire project. This chapter explained the procedure for recording the EEG activity, features extraction and data processing.

**Chapter 4** elucidates the qualitative and quantitative evaluation of the research finding including elaboration on the results of statistical analysis.

**Chapter 5** deliberates in-depth discussion and outcome of the research, comparing with previous findings, and it's significant.

Finally, **Chapter 6** concludes about the work done throughout the project in achieving the objective and explores implications for future direction.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Fundamental principal of human auditory system

The creation of sound waves correlates with the vibrations that transmit through the air or other medium and generated by the continuation of regular vibrations form. The sound wave characteristics absolutely contradict to noise wave since this is a form of perturbations wave caused by the agitation of energy coursing through a medium such as air, liquid or solid matter as it propagates away from the original sound (Cook et al., 1999; Ladefoged & Maddieson, 1998; Skagerstrand, Stenfelt, Arlinger, & Wikström, 2014). Sound overture living things a dominant means of communication. The ability of the auditory organ to perceived surroundings sounds through time by these air vibrations mechanism is known as auditory perception or audition (Schnupp, Nelken, & King, 2011). The human auditory system consists of two parts which are a peripheral auditory system which feeds on the mechanical apparatus behavior and central auditory system pertinent to the neurological interpretation of the acquired stimulus.

In simpler explanation, the auditory waves initially will be received by the ear canal in the form of compression pressure waves. These waves induce vibration to the eardrum and other structures attached to it and then will be transmitted to the middle ear followed by basilar membrane, hair cells, auditory nerves, brainstem and finally to the auditory cortex (Kemp, 1978). Figure 2.1 illustrated the coronal section anatomy of the human ear. The first phase of auditory stimuli conduction begins at the peripheral auditory system involving the mechanoelectrical transduction of sound pressure-wave into neural action potentials. The auditory system originated from the auditory sensory neuron provides a significant function towards perceiving and transmitting hearing stimuli from the peripheral level to the main processing area in the brain. These potentials will then trigger the nerve impulse and transmitted this auditory input into the cerebral cortex located in the central auditory system through the neural auditory pathway for encoding mechanism purpose. The brain works as a central processor of sensory impulses in which several sectors of the brain interacting all at once through a computational interpreting approach when it perceives the stimuli. The human ear could respond to frequencies underlie between 20 Hz to 20,000 Hz only, although most speech frequencies lie between 100 and 4000 Hz (Anderson et al., 2013; Syka, 2002; Tremblay, Piskosz, & Souza, 2002).

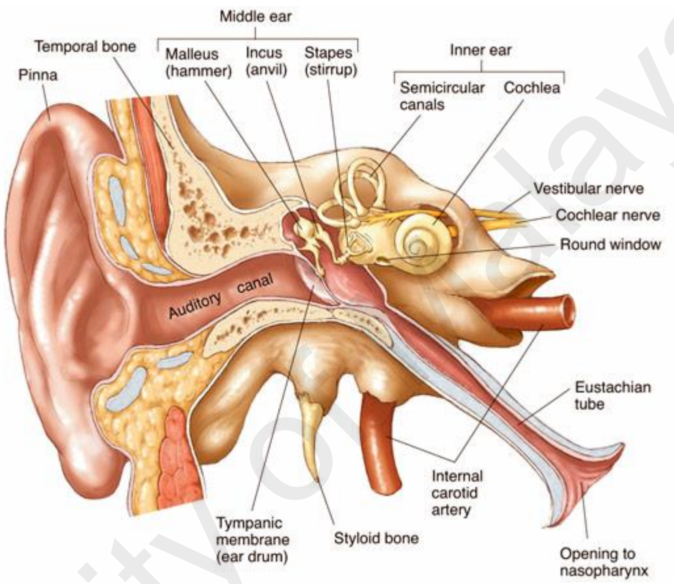


Figure 2.1: The coronal section of the head showing the anatomy of the ear (Chittka & Brockmann, 2005).

## 2.2 Hearing impairment, hearing aids and aural rehabilitation

Prolonged exposure to the frequency beyond acceptance limit will lead to hearing impairment which will definitely impede with the social and job-related interaction. On the basis of health-interview data in the United States population, they concluded that more than 4% of individual under 45 years old and approximately 29% of people greater than 65 years of age engaged with some level of hearing loss (Nadol, 1993). The same survey was done in Great Britain when they claimed that quarter of the population questioned undergoes some degree of hearing deficiency and 1/5 of them was reported to have more than 25 dB hearing deficits in the better-hearing ear when tested with audiometric measurements (Nadol, 1993). Hearing loss is considered as one of the most common complication faced by the elderly people reflecting the abnormalities of the neural pathways due to the deficit in the hearing encoding mechanism in the brain (Pfefferbaum, Ford, Roth, & Kopell, 1980; Tremblay, Piskosz, & Souza, 2003). It is undeniable that there is a great significant slippage in the auditory memory due to the fact that hearing loss is the typical impairment in elderly people. These changes in neural processes help to measure the encoding of neural correlates in an effort to repair the related neural plasticity after the on-set of any deficit (Moore, 1993; Neuman, 2005). The degree of hearing loss can be classified from mild to moderate and finally profound as illustrated in Figure 2.2, and in most cases, people face difficulties in speech perception and recognition (Akeroyd, 2008; Martin & Jerger, 2005; Stewart & Wingfield, 2009).

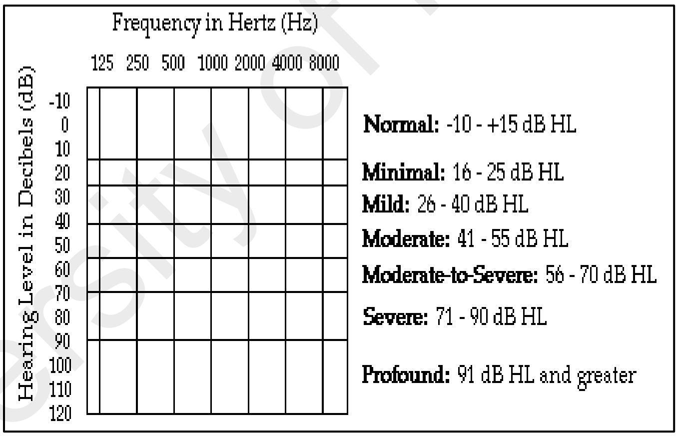


Figure 2.2: Degree of hearing loss from pure tone audiogram test (Fifer, 1997).

The severity of speech perception and recognition in the patient with hearing loss dependence on the brain’s ability to provide decent feedback to the ear, by filtering out unwanted and unnecessary information before decode them. The human environment and physical factors could danger our auditory sensory system which in severe cases can lead to the total deaf. They can result from sound exposure, heredity, aging or known as presbycusis, ototoxic drugs, trauma, disease or infection. The cross-sectional regions of two categories of hearing loss impairments which are conductive and sensorineural were demonstrated in Figure 2.1 (Clark, 1981; Duncan, Rhoades, & Fitzpatrick, 2014; Gordon-Salant, 2014; Liu & Yan, 2007). Conductive hearing loss causes by any damage or malfunction of the outer or middle region ear and SNHL correlates with the damage on the nerve fibers located in the inner ear so-called nerve-related hearing loss. Some possible reasons for conductive hearing loss are the perforated tympanic membranes, present of fluid in the middle ear, ear infections (otitis media), allergies, benign tumours, the presence of foreign object and the malformation of the outer structure of the ear (König, Schaette, Kempter, & Gross, 2006). The causes for SNHL are most likely due to the aging factor, exposure to excessive loud, malformation of the inner ear structure, illnesses, heredity and drugs consume (König et al., 2006). Mixed type hearing loss combined both these factors and in some cases cause hearing deafness. A recent study highlighted the dissatisfaction of SNHL population when they experienced some increment in the speech intensity without speech intelligibility during the noisy situation which emphasized the significant of depth understanding of human speech perception which extends beyond reduce audibility (Anderson et al., 2013).

Formerly, researchers introduced hearing aids devices with enlargement of the amplitude when receiving stimulus but its deviates from the main objective when SNHL population reported the failure of the device which do not foster speech clarity in communication (Boothroyd, 1993; Korczak, Kurtzberg, & Stapells, 2005b). Fully functional adoption of hearing aid devices are stated to be still low as per statistics (Golder, Walsh, Buchanan, & Lind, 2012; Wolfe, 2011). Despite the implementation of high technological hearing devices, individuals with SNHL report dissatisfaction due to intelligibility disruption to the desired signal perception especially in the noisy circumstances, thus contribute to the main hindrance in the device abandonment (Anderson et al., 2013; Gordon-Salant, 2014; Skagerstrand et al., 2014). This evidences there still remains a significant gap between the most advanced hearing aids and the human body, showing the need for a mechanism to motivate usage of hearing device by the user. The realization in a reduction of quality of life and far-reaching consequences for the individual concerned due to hearing impairment, vast interest had been done to overcome this phenomenon. The introduction of aural rehabilitation technique increases the tendency to eliminate hearing-loss-induced deficits of activity, participation and quality of life (Boothroyd, 1993; Henoch, 1991). In fact, the main approach is done by this technique through the combination of sensory management, perceptual training, instruction and counselling able to indirectly addresses the psychosocial issues surrounding acquired hearing loss population (Boothroyd, 2007; Wayner, 2005). The previous study highlighted the effectiveness of aural rehabilitation in motivated and encouraged hearing aids users to maximize fully functional of the hearing device in an effective way (Collins, Liu, Taylor, Souza, & Yueh, 2013). Last study also concluded the significant improvement in the cochlear implant patients on speech perception performance based on the moderate auditory training as shown in Figure 2.3 (Fu, Galvin, Wang, & Nogaki, 2005).

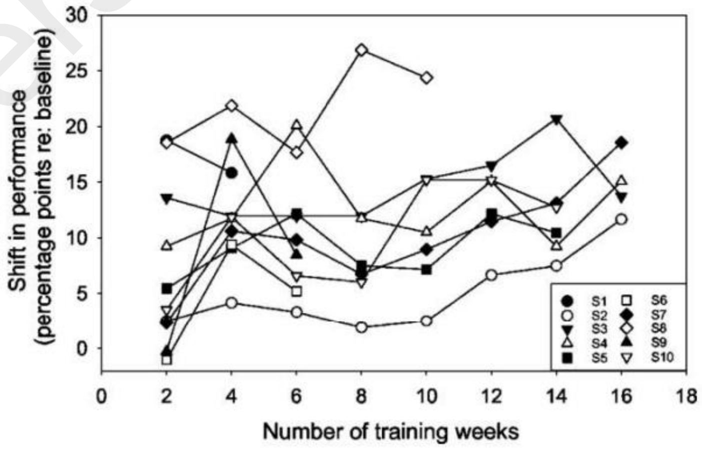


Figure 2.3: Vowel recognition performance during the moderate auditory training period for each individual subject (Fu et al., 2005).

Recent investigators highlighted the most typical SNHL disease known as tinnitus which having a direct relationship with the functional adjustment of the central auditory and non-auditory arrangement in sensation processing aspect (Gerken, Hesse, & Wiorkowski, 2001; Rauschecker, 1999). Specifically, tinnitus linked to the abnormal noise or ringing sound in the ears underlying to several difficulties in concentrating, sleeping, and speech recognition and perception as the impact of acutely sensitive organ to sound stimulus (hyperacusis). At the same time, the mechanism of auditory end organs induced the primary changes for tinnitus so-called plasticity changes which finally deviate the desire neural functionality in terms of sensation processing of the cortical and subcortical structures of the auditory and non-auditory nervous system (Manchaiah, Baguley, Pyykkö, Kentala, & Levo, 2015; Moore, 2010). Tinnitus affects 10%-30% of the population and tends to increase in frequency with age (König et al., 2006). As most tinnitus patients have various degrees of associated hearing loss, speculate theory convinced the existence of peripheral hearing deficiency providing an imperative prerequisite for the tinnitus episode. However, divergent findings question the capacity of mild peripheral hearing loss to trigger auditory cortical reorganization. Thus, with regard to the changes of activity in the central auditory system, the differences between tinnitus patients with and without hearing loss remain unclear (Manchaiah et al., 2015; Walpurger, Hebing-Lennartz, Denecke, & Pietrowsky, 2003).

Though the cause of hearing loss due to various diseases and reasons are reported in the literature, the exact roles of these reasons in changing the auditory neuron processes are yet not clear. Previous study done on the United States population showed that up to 40 to 45 % of elderly people older than 60 years old experience some degrees of hearing loss, this range increases to 83% for more than 70 years old people (Gordon-Salant, 2005, 2014; Tremblay & Burkard, 2007) and it is predicted that in 2030, 44 million people in the United State of America have some degrees of hearing loss (Kochkin, 2005a, 2005b).

The success rate of usage for even the best suitably chosen hearing aids or implants depends upon not only the role of skill development programs but the possible chance for revival of the necessary neural processes for encoding hearing interpretations in the brain.

## 2.3 Overview on Electroencephalography

The brain is probably the most complex sophisticated structure in the known universe. The brain consists of highly specific division to compensate with various operations including vision and memory. While these parts work together, each part is responsible for a specific function. To understand the functional status of the brain such as in sleep, anesthesia, hypoxia (lack of oxygen) and in certain nervous diseases, e.g. epilepsy, the brain's recordable neuroelectric signals, called electroencephalogram (EEG), are processed and analyzed (McCarthy & Wood, 1985; Picton et al., 2000; Sams, Paavilainen, Alho, & Näätänen, 1985). Electroencephalography is used to record the electrical activity of billions of polarized neurons within the cerebral cortex at specific locations across the scalp (Martin & Boothroyd, 2000; Martin, Barajas, Fernandez, & Torres, 1988; Näätänen, 1995; Ponton et al., 2001). The EEG recording was first discovered by a German psychiatrist named Hans Berger in 1929 (Gloor, 1969). The EEG signals are commonly measured from the scalp surface by using scalp electrodes referred to the international 10/20 electrode system. EEG recordings are also obtained from 32, 64, 128, or 256 channel EEG electrode systems for source localization purposes. The spectral classification of the EEG consists of four bands (Başar, Gönder, & Ungan, 1976): δ (delta) activities vary from 0.5 to 3.5 Hz. They are rare and are often considered pathological when observed in the normal waking adult with high amplitude. Θ (theta) activities vary from 3 to 8 Hz. During sleep, these waves are usually more prominent in the temporal areas of the brain. α (alpha) waves vary from 8 to 13 Hz. They are prominent in the occipital region of the brain when the person is relaxed with eyes closed. β (beta) activities vary from 14-30 Hz. Their amplitudes range from 5μVolt to 20μVolt. They are commonly seen in the frontal and central regions of the brain. Finally, the γ (Gamma) wave recorded between 30-100 Hz. Figure 2.4 displayed the typical electroencephalography montage placement and Table 2.1 showed the spectral bandwidths of EEG signal appearances and the behavioral trait at each spectral frequency rhythm.

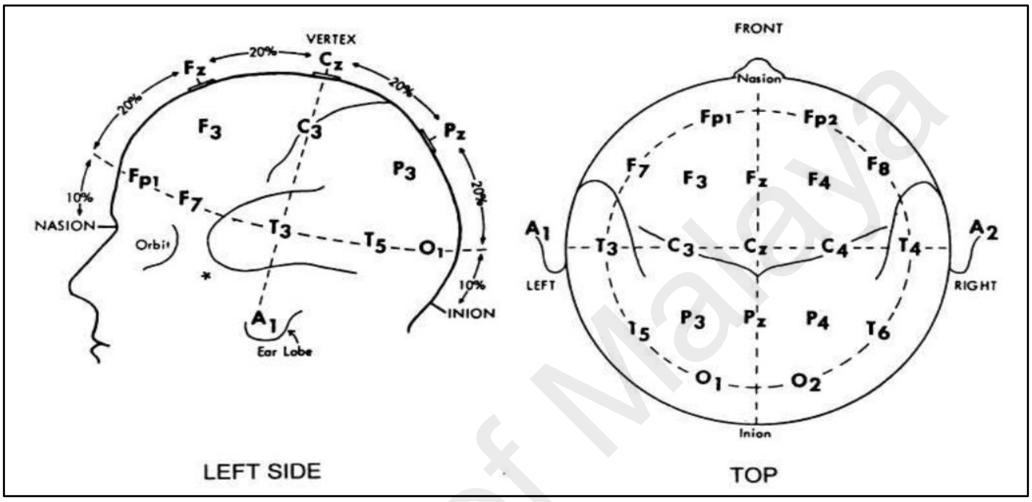


Figure 2.4: The electroencephalography montage placement based on the international 10/20 electrode placement system (Simpson, 1974).

Table 2.1: The spectral analysis of EEG signals and the main behavioral trait for each respective spectral bandwidth

| Rhythm | Signal appearance | Main behavioral trait |
|---|---|---|
| Gamma 30-100 Hz | | Represents binding of different populations of neurons for the purpose of carrying out a certain |
| Beta 13-30 Hz | | Usual waking rhythm associated with active thinking and active |
| Alpha 8-13 Hz | | It is usually found over the occipital regions. Indicates relaxed awareness without attention or |
| Theta 4-8 Hz | | Theta waves appear as consciousness slips towards drowsiness. Theta increases have |
| Delta 1-4 Hz | | Primarily associated with deep (slow) wave sleep. |

(Başar, Başar-Eroğlu, Karakaş, & Schürmann, 1999; Basar, Rosen, Basar-Eroglu, & Greitschus, 1987).

The application of EEG signal in a clinical sector has gone through drastic changes over the last century when it is recognized as powerful tools in understanding various clinical function including cognitive neuroscience such as memory, decision-making, perceptual-motor functions and performing the discriminant task.

## 2.4 Implication on Event-Related Potential (ERP)

The brain electrical activity, that occurs in association with an external stimulus (auditory, visual or somatosensory), is called Evoked Potential (EP). If the experiment is relevant to a cognitive activity, the response signal is frequently called as either event-related-potential (ERP) or cognitive EP in a wide range of cognitive paradigms. EPs are important diagnostic tools in the investigation of a physiological and psychological situation of subjects (Duncan et al., 2009; Stapells, 2002). EPs or ERPs are not recognizable by visual inspection since they are buried in spontaneous EEG with a signal-to-noise ratio (SNR) as low as −5 dB considering stimulus-unrelated background EEG as the noise in the measurements (Picton, Lins, & Scherg, 1995). Restated, ERPs comprise of electrical neuron changes in the EEG signal recorded from the brain responses that are time-locked mechanism to an event of stimuli. Distinct category of evoked potential (EP) leads to various neurological functions; i.e. the CAEPs substantiate with the appraisers of the incoming auditory stimulus from ears through the auditory nerve pathway to the brainstem, besides that, the visual evoked potentials (VEP) correspond in evaluation of the stimulus originated from the eyes to the occipital cortex region in the brain through the visual nervous system and finally the somatosensory evoked potentials (SEP) which posit the nerve pathways coming from the arms or legs by passing through the spinal cord to the last central operation which is brainstem or cerebral cortex.

In the present research, we are interested to discover the significant of CAEP on the various speech phonological features on the SNHL patient. Basically, CAEP monitored the voltage deflection within the tracking time indicates the allocation of neural resources to specific cognitive function, i.e. the deviation could direct to hypothesize several brain dysfunctions based on the amplitude and latency analysis (Duncan et al., 2009). Figure 2.5 presented the late CAEP components in response to auditory stimuli.

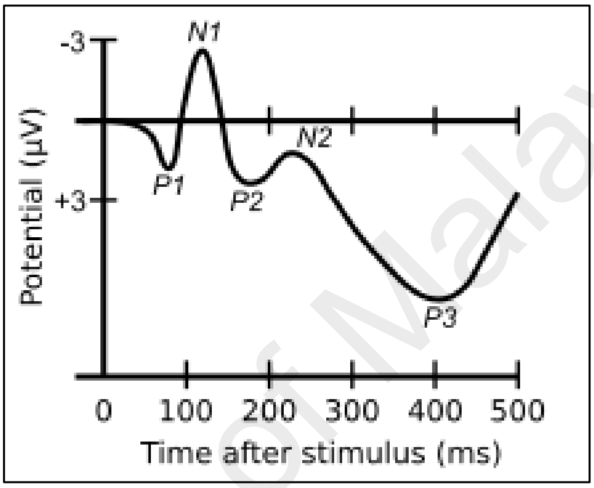


Figure 2.5: Late CAEP components after stimulus onset (Roets-Merken et al., 2014).

Formerly, VEP was discovered in 1934 when Adrian and Matthew evidence some alteration in the action potential after the onset of light stimulation at the occipital region. Extensive exploration in developing the theory of VEP is keep improving when recently in 2014, VEP P2 component was analyzed to diagnose Alzheimer's disease and concluded that the prolonged latency of P2 flash component might be reliable in understanding the human visual system pathologies related to Alzheimer's disease (Coburn, Arruda, Estes, & Amoss, 2014). In last year, VEP was used as a precursor in the neurophysiological evaluation of women suffering from pre-eclampsia (Brussé, van den Berg, Duvekot, & Visser, 2015). The evolvement of CAEPs increases in parallel with VEP and not lagged behind when more strides were done in developing the knowledge for the last decade. Previous researcher measured the distinct neural activation patterns using a functional magnetic resonance imaging (fMRI) technique in concatenation of three vowels and three speakers within varying acoustic conditions for the purpose of understanding the brain decode mechanism through CAEP components (Bonte, Hausfeld, Scharke, Valente, & Formisano, 2014). Much interest was done by previous scientist's when they tried to discover the impact of speech perception and discriminant task on people suffer from autism and misophonia disease and the significant of the finding to provide better mechanism for treatment purpose (Modugumudi, Santhosh, & Anand, 2013; Oberman et al., 2005; Schröder et al., 2014). Last year, depth exploration was done by Arsenault and Buchsbaum (2015) when they emphasized the neural pattern representations related to perceptual confusability in terms of "psychological space" organization associated with the CAEP (Arsenault & Buchsbaum, 2015). CAEP analysis was also done on the chronic Schizophrenia patient when scientist examined great reduction of N1 and P2 components in response to attended tones stimuli (Salisbury, Collins, & McCarley, 2009).

The separation of the EP (the signal) and the ongoing EEG (the noise) in the measurements have been very attractive research area. This requires use of powerful signal processing tools and several methods have been proposed for this purpose. The holistic explanation on how the sound interpretation and perception resulting understanding during interaction which coincides with the imprecision of the language is far from complete. More efforts have done by scientists to discovered the brain decode mechanism in understanding and interpreting language structure accuracy besides variability of listening skills to compensate for daily environment as so to impart better rehabilitation mechanism for those suffer from hearing impairment (Arsenault & Buchsbaum, 2015; Billings, Tremblay, Souza, & Binns, 2007; Korczak & Stapells, 2010; Schröder et al., 2014; Ylinen, Shestakova, Huotilainen, Alku, & Näätänen, 2006).

## 2.5 Exploration on speech cues in acoustical perception

### 2.5.1 Features of speech articulation

Characteristics of various speech cues provide a broad efficacy towards understanding spoken language, discriminate and recognize the salient information in the speech signal during human interaction, so called speech perception (Korczak & Stapells, 2010; Mji, 2001; Wunderlich & Cone-Wesson, 2001). These acoustic phonological features such as voice/voiceless discrimination, place, and manner of articulation provide a crucial complexity mapping mechanism which creates a stable neuronal representation in the human auditory system when perceiving language structure (Arsenault & Buchsbaum, 2015). The types of articulatory phonologic features are classified based on the nature constriction factor of air in the vocal tract which determined the acoustical qualities of the consonant as shown in Table 2.2 (Arsenault & Buchsbaum, 2015; Gordon-Salant, 2014; Jaramillo et al., 2001; Ting, Chia, Hamid, & Mukari, 2011). Place of articulation feature confounding with the obstructive occurrence when two articulators closer to each other. Manner of articulation represents the speech organs besides the location of the constriction or obstruction. Finally, the voicing contrast which characterized by the 'voiced' sound caused by the vibration of the vocal cords which are close to each other and the 'unvoiced/voiceless' sound induce due to the turbulence incident.

Speech cues indicate the essential acoustic patterns of speech that help the listener to perceive a phoneme in a word, phrase or sentences. For several years, researchers and investigators have made significant strides in this endeavor to set up the acoustic cues that are crucial to the perception of specific phenomes; as such various speech cues typically exist within a word, for each specific phoneme. Collectively, previous finding emphasized the significant of spectral and temporal cues as the most influential acoustic cues for speech understanding. Determination of place and manner of articulation provide efficacy in differentiating between consonants phenomes. Notwithstanding, the advent of formant transition lead to the perception of glide consonants, which produce by articulatory motions that occur when the vocal tract is markedly narrow, but not closed.

Table 2.2: Phonetics features of speech articulation for consonant sound

| | Bilabial | Labio-Dental | Inter-Dental | Alveolar | Alveo-Palatal | Palatal | Velar | Glottal |
|---|---|---|---|---|---|---|---|---|
| **Stop (oral)** | | | | | | | | |
| voiceleess | p | | | t | | | k | |
| voiced | b | | | d | | | g | |
| **Nasal (stop)** | m | | | n | | | ŋ | |
| **Fricative** | | | | | | | | |
| voiceless | | f | θ | s | ʃ | | | h1 |
| voiced | | v | ð | z | ʒ | | | |
| **Affricate** | | | | | | | | |
| voiceless | | | | | t͡ʃ | | | |
| voiced | | | | | d͡ʒ | | | |
| **Glide** | | | | | | | | |
| voiceless | ʍ | | | | | | ʍ | h1 |
| voiced | w | | | | | j | w | |
| **Liquid** | | | | | l r | | | |

(Cook et al., 1999).

### 2.5.2 Spectral and temporal cues

Spectral cues engage with the formant frequencies and formant transitions which are the most crucial aspects in contributing the sound spectrum energy in a particular speech phenome. Formant frequencies defined as the resonant frequencies of the vocal tract during the creation of vowels and consonants sound. Rapid frequency spectrum changes occur within a certain period of time and reflected by the motion of vocal tract to alter the constriction gap during consonant sound production known as formant transitions. Contrary, several important spectral cues were revealed during vowel perception. For example, a vowel is generated when the glottal source is created and air passage is relatively un-obstructed. Detection of spectral peaks known as formant frequencies for specific vowel was performed by the resonance of the vocal tract during the production. Last studies highlighted the methodical shifting on vowels sound for the first three formant frequencies due to the articulatory position changes as these frequencies are defined as the most important elements in differentiating and recognizing vowels compared to the others phonemes. For example, the high front vowel /i/ is characterized by a low first formant (F1) and high second formant (F2), while the low back vowel /a/ is characterized by a high F1 and low F2 value (Peterson & Barney, 1952). Delattre, Liberman, Cooper, and Gerstman (1952) evidences the steady-state formant frequencies of various synthetic vowels and found that participants frequently required only the first and second formants to accurately recognize a vowel.

Regarding the manner of articulation properties contrast, nasal consonants are produced by occluding the oral cavity and letting the sound radiate through the nasal cavity. Acoustically, nasals are identified as having a low-frequency resonance or murmur sound that characterized by a spectrum frequency below that 300 Hz and highly attenuated in intensity at greater formants, which in general classified them as weak sounds due to the complete closure of the oral cavity. In spite of that, murmur sound acts as a predominant cue to the nasal manner of articulation during sound production.

Another manner of articulatory properties elucidates by the fricative consonants sound. They are created by the duress of air through the constriction of the vocal tract forming turbulence breath stream resulting in a noise-like sound. Specifically, the continuation of strong and energetic turbulence force within the high-frequency resonance above 4 kHz associated with the properties of alveolar fricatives consonants sound. A stop is produced by a complete occlusion of the vocal tract, resulting in a temporary cessation of airflow, typically followed by a release consisting of a transient burst of noise. Engagement of formant 2 (F2) transitions frequencies and the spectral peak frequency of the noise burst production provide main contrast in categorizing place of articulation of the stop consonants from other classes. Last studies done by Stevens and Blumstein (1978) revealed the significant finding when they highlighted the specific frequency range of each labial, alveolar and velar articulation represented by /b/, /d/, and /g/ consonants respectively. They conclude that the velar consonants having denser properties with an accumulation of energy within the middle-frequency range. Both labial and alveolar consonants experienced the same results when the energy was spread out but opposite pattern was engaged with the alveolar consonants when they exert at high-frequency range instead of a low-level range as presented in labial consonants sound.

Voice onset time (VOT) involve the transition period between the burst of plosive (release) and the voicing onset of the following vowel and it is considered as a prerequisite element in understanding the temporal perception of initial stop consonants. In the production of a syllable-initial stop, there is a closure phase and a release phase. The duration, measured from the time of the release burst to the onset of periodic vibrations observable in formant 1 (F1), provides important cues for the differentiation of initial voiced and voiceless stop consonants. Notwithstanding all these articulation presentations help the human to organized neurologically and manipulate with various speech structure and jargon segment within the context of complexity spoke language which finally attribute to speech intelligibility and perceptual understanding (Arsenault & Buchsbaum, 2015; Korczak & Stapells, 2010). To summarize, recognition of segmental phonemes required important cues known as spectral information even in static nor dynamic form. Due to that, the exploration of speech understanding involving depth review on the frequency resolution would be crucial in order to effectively enhance the knowledge on recognition of segmental phonemes despite they are still lagged behind.

## 2.6 Perceptual understanding of human CAEP components on tonal and speech stimuli

Human social interaction requires hearing ability to communicate through language, speech and acoustic patterns that vary in frequency and intensity. During development, the human brain continuously trained to undergo adaptive process within the surroundings and tend to effortlessly discriminate speech components of their first language better than their second language (Korczak & Stapells, 2010; Oates et al., 2002b; Steinhauer, 2014; Ylinen et al., 2006; Zheng, Minett, Peng, & Wang, 2012). The ability of human nature to selectively distinguish between desired and interfered phonological features goes around them is quite successful. However, CAEP constituting the neuronal linguistic complexity associated with words and sentences, depends entirely on the frequency resolution so as to discriminate with the desired neural pattern of perception. Frequency resolution indicates the capability to selectively resolve or isolate the sound complexity based on the individual frequency components. Lutman, Gatehouse, and Worthington (1991) investigated the degradation of frequency resolution of large groups of listeners with different levels of SNHL. His finding suggests that frequency resolution capability deteriorates progressively with an enlargement hearing threshold level. Indeed, SNHL correlates with some potential deprivation in the auditory speech processing mechanism of the cerebral cortex which corresponds in slowing down the cortical remodeling for improvement in auditory responses. The components of CAEP engage with the intricate pattern of brain processing response of complexity stimulus which correlates with the decision making or reasoning (Davies, Chang, & Gavin, 2010). Speech-sound recognition difficulty associated with the imbalance of cortical deviation in the balance of excitation and inhibition of auditory neural networks which causes a resurgence of hearing problem.

Basically, ERPs are electrophysiological responses to sensory, motor, or cognitive stimuli and reflect perceptual processes in the brain cortex (Pratt et al., 2009; Schröder et al., 2014; Steinhauer, 2014; Wunderlich & Cone-Wesson, 2001). Many researchers have used the CAEP to measure the neurophysiological correlates of perceptual responses to auditory stimuli which could be presented to the participants as tones, speech (consonant-vowels), words or music stimuli. In 2011, Anderson and Kraus revealed the subcortical responses of auditory processing ability in dealing with speech-in-noise conditions reflected by the neural encoding of pitch, timing, timbre and the crucial elements of speech and music on individuals suffer from hearing deficits (Anderson & Kraus, 2011). They found that the speech-in-noise enhance the perceptual ability and conclude that musical training able to improve the damage done by the background noise on speech understanding. More interests have done on tonal stimuli to discover the brain auditory response using CAEP analysis. Last investigator used high and low frequencies tones to define the cortical brain responses on CAEP components. Collectively, they proposed that N1 component highly activated at the temporo-parietal auditory areas and this component together with P2 elicited double peak on bilateral and right temporal sites. The researchers conclude that the human auditory activation depends on the base frequency, magnitude and the frequency change direction (Pratt et al., 2009). Earlier, investigators tried to compare the intensity dependence at selected frequencies between the tinnitus subjects with the normal hearing listener using CAEP study. The authors demonstrated contradict increment on the intensity dependence of N1 and P2 component at selected frequencies seen in tinnitus group in comparison with the normal subject as shown in Figure 2.6 (Lee, Jaw, Pan, Lin, & Young, 2007). The CAEPs provides insight into the neural mechanisms underlying speech processing (Carpenter & Shahin, 2013; Gordon-Salant, 2014; Tremblay et al., 2002). Consequently, vast amount of electrophysiological investigation tries to discover how these speech articulatory features are represented in CAEPs components in people with hearing loss through a distinct pattern of distinguishability between individual's phenomes.

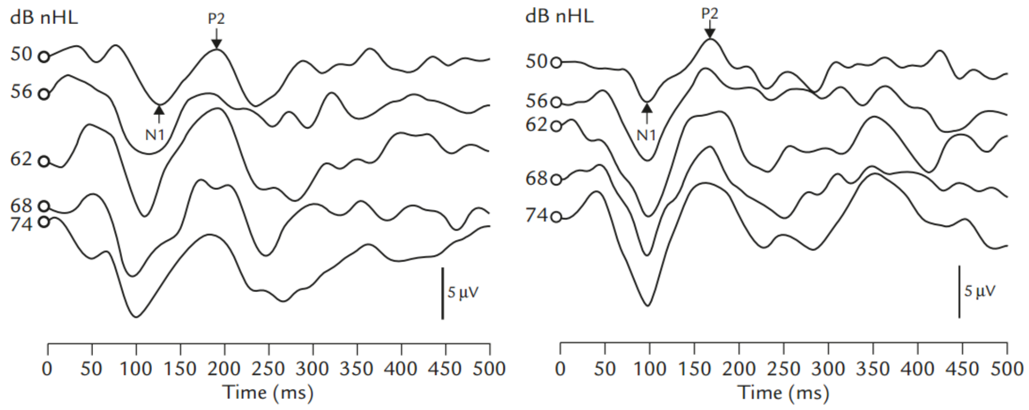


Figure 2.6: Average CAEP N1-P2 components recorded at Cz electrode using 1000 Hz tone burst stimuli at five different intensities (50, 56, 62, 68 and 74 dB). Left: A healthy subject without tinnitus. Right: A tinnitus patient with normal hearing (Duncan et al., 2009).

To date, a convergence of interest in understanding the correlation of speech recognition difficulties and brain auditory system interpretation of phonological features through CAEPs and magnetoencephalography (MEG) techniques. Earlier studies have established the efficacy of CAEPs components in examining the human auditory process and speech complexity discrimination involving normal hearing individuals as well as people suffering from hearing complication (Csepe & Molnar, 1997; Duncan et al., 2009; Schröder et al., 2014). A number of preliminary studies demonstrated the contribution of elicited CAEPs building blocks by tonal stimulus (Jacobson et al., 1996; Jacobson, Lombardi, Gibbens, Ahmad, & Newman, 1992; Sams et al., 1985) and naturally produced CV syllables (Agung, Purdy, McMahon, & Newall, 2006; Arsenault & Buchsbaum, 2015; Korczak & Stapells, 2010; Obleser, Lahiri, & Eulitz, 2004) providing the evidence of CAEP efficacy in established entire speech frequency range. Earlier studied indicates that the adversity of speech perception depends upon the increment time – varying acoustic cues of the speech tokens due to the high sensitivity level of imperative cortical CAEPs responds against speech structures. The result obtained previously proposed that the accretion VOT for the voiced /da/ token and voiceless /ta/ stimuli created double negative peaks (N1 and N1') within the first 100 ms late latency response compared to single negative peak corresponds for shorter VOTs outlining the complementation of time-varying acoustic cues and neural perception synchrony  (Korczak & Stapells, 2010; Sharma, Marsh, & Dorman, 2000).

Further evidence was illustrated previously when scientists found the overlapping mechanism of P1-N1-P2 complexes from the acoustical transition of consonant to vowel in monosyllables CV stimulus (Ostroff et al., 1998). Same evidence was also found in 2003 when distinct cortical morphology patterns were evoked by the syllables stimuli differed in their initial phenomes /bi pi si ʃi/ (Tremblay, Friesen, Martin, & Wright, 2003). In 2006, researchers summarized the production of N1 and P2 components which entirely depends on the changes of frequency energy of the incoming speech sounds stimuli (Agung et al., 2006). Last year, Arsenault and Buchsbaum (2015) represented the dispersion of neural categorical features of speech articulation surrounding the bilateral primary and secondary besides areas of the superior temporal cortex instead of motor cortex using functional magnetic resonance imaging (fMRI) analysis. This is a continuation of the recent study when investigators showed some potentials areas located on the left superior temporal gyrus (STG) which is responsive towards certain speech articulation features (Mesgarani, Cheung, Johnson, & Chang, 2014).  In 2002, Oates et al. (2002b) discovered the impact of SNHL individuals on the cortical behavioral mechanism in response to place of articulation stimuli (/ba/ and /da/) presented at different intensity level. This finding suggests that the behavioral discrimination scores and CAEP amplitudes were relatively lower in sensorineural group besides some prolonged latencies responses. In addition, the amplitudes and latencies of P3 and N2 components were greater in SNHL population compared to N1 and MMN responses.

More depth exploration was done in 2005 when the authors determined the impact of personal hearing aids on CAEP components using the same set of stimulus as in 2002 (Korczak et al., 2005b). In this study, they conclude that the personal hearing aids able to effectively improve the speech perceptual and understanding of the hearing-impaired group even at a lower level intensity but depends entirely on the severity level of hearing impairment. Similarly, further attempt made by Korczak and Stapells (2010) in understanding the brain auditory response towards three types of speech phonological features on SNHL population. Interestingly, P3b and reaction time (RT) components showed smaller latencies in responses to the vowel versus consonant contrast. They conclude that the significant of frequency spectral changes underlying the reason of larger responses to the vowel contrast illustrated by the CAEP amplitudes parameter. More efforts had emphasized the necessity of CAEP components indexed by the MMN and P3b analysis underlying the speech discriminate process during passive listening conditions through neural distinguishing of salient and deviant acoustic signals (Collins et al., 2013; Tavabi et al., 2009; Ylinen et al., 2006). Formally, scientist discovered the internal neural speech discrimination of the brain through active listening condition of school-aged children between 7 to 12 years' age and concluded that such theory will provide a novel basis towards speech perception abilities in clinical implementation (Martin & Boothroyd, 2000; Martin et al., 1988; Taylor, 1988). Earlier studies also explained the significant of using speech complexity in understanding the conscious auditory mapping mechanism during active listening compared to the passive condition to compensate with the everyday listening phenomenon (Picton et al., 2000).

### 2.7 The Mismatch Negativity (MMN) response

The MMN response is a passively-elicited component of the CAEP. It reflects preattentive identification of infrequent changes in the acoustic stimuli (Näätänen, 2001). The MMN is elicited using a different paradigm in which an auditory standard stimulus is presented repeatedly to the listener. A deviant stimulus is occasionally presented in a random fashion, replacing the standard stimulus (Duncan et al., 2009; Jacobsen, 2004). The MMN response is enhanced or attenuated depending on the extent of the difference between the standard and the deviant stimuli. While several studies have shown that the MMN response is evoked by both speech and non-speech stimuli, some researchers have asserted that the MMN is only evoked by non-speech stimuli (Tampas, Harkrider, & Hedrick, 2005). Becker and Reinvang (2007) demonstrated that natural speech sounds can elicit MMN responses, thereby concluding that the MMN detects both non-phonetic and phonetic changes in speech. In another study, MMN responses were elicited in infants through the use of recorded speech sounds (Cheour et al., 1998). However, most auditory EP studies to date have presented listeners with synthesized speech with the intent of studying the brain's response to very specific frequencies in the speech sound. Aaltonen et al. (2008) presented participants with speech stimuli and elicited MMN responses through the intermittent violation of phonological constraints. Amplitudes of the MMN were greater for violations considered more deviant in the English language, thereby showing that the MMN response has some linguistic components. Thus, the MMN cannot be solely attributed to acoustic processing and perception. The mainstream interpretation of MMN usage in clinical application begins in the late 1990s when it provides a potential means for measuring possible auditory perception and sensory-memory anomalies (Näätänen, Paavilainen, Titinen, Jiang, & Alho, 1993). The introduction of MMN and its relationship with CAEP responses were still in the early stage of justification (Jacobsen, Schröger, Horenkamp, & Winkler, 2003; Näätänen et al., 1993). Some researchers highlighted that CAEPs responses and MMN as a method in understanding how brain interpreted between different speech signals, and thus indicated that they were no interrelationship between these responses (Becker & Reinvang, 2007, 2013). Previous researchers concluded that the human auditory system elicited greater brain response towards speech CV stimuli compared to tonal stimuli as reflected in higher MMN and P3a amplitude values (Jaramillo et al., 2001; Tavabi et al., 2009). Former studies also proposed that the enlargement of MMN amplitudes in native speakers with two non-native speaker groups indicates the activation of native-language phonetic prototypes (Picton et al., 1995; Ylinen et al., 2006)

It is reported the effectiveness of MMN amplitude towards categorical phonemes and frequency deviation in the speech perception emphasize the neural changes encode by the cortical auditory event potential (Tavabi et al., 2009). More recently, researchers manifested the abilities of human auditory system to distinguish between distinct phenomes behavioral categorization and the dependency of individual's first native language based on the MMN amplitude analysis (Ylinen et al., 2006). More progression was done by Näätänen (2008) sought to determine whether the preattentive processing of natural speech sounds is in any way attributable to early speech processing within the cortex. They presented the Finnish phoneme /e/ and the Estonian phoneme /o/ to Finnish subjects with no prior knowledge of the Estonian language and found the MMN response to be greater after the presentation of a Finnish deviant stimulus, as opposed to the presentation of an Estonian deviant stimulus. The authors concluded that language-dependent memory traces exist and are activated within 200 ms after the onset of speech stimuli. The same language-dependent memory traces are not activated when acoustic non-speech stimuli are presented to the listener, even if the stimuli are acoustically equally complex. Similar study by Edmonds et al. (2010) concluded that speech-specific processing may involve the primary auditory cortex, or even subcortical structures, and could influence early CAEPs such as the MMN response. The authors reported not only that the MMN response reflects early speech processing, but also that formant information in steady-state vowels is the primary contributor to speech processing, thereby supporting a formant-based phonemic theory of preattentive processing of natural speech sounds. In contrast to the aforementioned findings, Tampas et al. (2005) reported that the MMN response is not influenced by the phonetic characteristics of the stimulus. They concluded that the MMN is purely reflective of an acoustic level of preattentive processing of natural speech sounds. Additionally, they concluded that the MMN response cannot be elicited at all by speech stimuli. The results conflict with those reported in the previously cited studies. Korczak and Stapells (2010) then investigate the significant of MMN response on various speech phonological features using the naturally speech sound so as to assert the distinguish properties of human brain in responds to different acoustical properties between and across features of speech articulation. They confirmed that the place of articulation experienced with some difference in MMN amplitudes which likely related to the phenomenon of frequency changes detection between the stimuli by the MMN responds.

## 2.8 Related research

In general, there have been some studies where the combined effects of SNHL and personal hearing aids on CAEPs between various articulatory features of speech were investigated. A very former study (Rapin & Graziani, 1967a) found that the majority (5/8) of their 5-to-24-month-old infants with severe-profound sensorineural impairments had aided CAEPs thresholds to click and tonal stimuli that were at least 20 dB better (lower) in comparison to their unaided thresholds. Another noteworthy finding presented by Rapin and Graziani (1967b) is that there is an increase in CAEP amplitudes when a child with hearing loss was aided. Last decades study also highlighted the variant dependent of different types of hearing loss with the effects on amplitudes and latencies of CAEP components. They conclude that the CAEP amplitudes were more affected compared to the latencies and this finding varies with types of hearing loss (Korczak, Kurtzberg, & Stapells, 2005a; Oates, Kurtzberg, & Stapells, 2002a). Billings et al. (2007) presented a 1 kHz tone to 13 normal-hearing young adults at 7 different stimulus levels, both aided (20 dB amplification) and unaided. There were no significant finding on the CAEP amplitudes after the amplification but the CAEP latencies oppose the same pattern.

Previous study was done by Oates et al. (2002b) involved 14 volunteers experienced with some degree of hearing loss. The study emphasized the detectability of hearing impaired individuals towards two distinct syllables /ba/ and /da/ presented at two different intensities (low at 65 dB and high at 80 dB SPL) on CAEPs. The result outlined low level of activation on the behavioral discrimination scores experienced by the normal hearing population. These differences in response strength were only true in hearing loss exceeding 60 dB for lower intensity stimuli and exceeding 75 dB hearing loss for higher intensity stimuli. The amplitude and latency response changes that occurred with SNHL were significantly greater for the later CAEP peaks (N2 and P3) and behavioral discrimination measures (d' and RT) in comparison with earlier (N1 and MMN) responses. Finally, they recommended future direction of the work to focus on the beneficial CAEP components that would be crucial for the clinician and the audiologist to understand the speech discrimination and intelligibility processing of individuals suffering from SNHL.

More recently, scientist discovered the effects of various features of speech articulation CAEP response involving SNHL population (Korczak & Stapells, 2010). To contrast with the previous experimental design, the CAEPs were collected from 20 subjects having normal hearing sensitivity on three sets of CV speech stimuli which are /bi/ versus /bu/,

/ba/ versus /da/, and /da/ versus /ta/. As a continuation of the previous study, each CV stimulus was presented at two different intensities which are 65 dB and 80 dB SPL. They manifested that all CAEP components were activated at a higher level in response to vowel contrast. In terms of latencies, the mean MMN, P3b and RT components showed earlier time responses to the vowel versus consonant contrasts. They conclude that the measurements of response strength (amplitudes) and response timing (latencies) for the various CAEPs suggest that the brain may have an easier task processing the steady state information present in the vowel stimuli in comparison with the rapidly changing formant transitions in the consonant stimuli. Thus, the main purpose of the present study was to determine the effect of CAEP response on the normal hearing adult with SNHL population between various speech phonological features in assessing speech detection and discrimination abilities of the human auditory system. Some of the work that has been done related to this study are summarized in Table 2.3 below.

Table 2.3: Summary on work done related to project

| Research title | Authors | Year | Subject and stimuli | Results |
|---|---|---|---|---|
| Effects of stimulus frequency and complexity on the mismatch negativity and other components of the cortical auditory-evoked potential | Julia L. Wunderlich and Barbara K. Cone-Wesson | 2001 | 12 healthy subjects with normal hearing threshold were tested with tone bursts in the speech frequency range (400/440, 1500/1650, and 3000/3300 Hz), words (/bab/vs /dad/) and CVs (/ba/ vs /da/) | MMN was exist between the ranges of 46%-71% of tests for the tone contrast paradigm, however attenuated to 25%-32% for speech contrast response. Similarities happened on the activation of N1 and MMN components for tones contrast. |

| Research title | Authors | Year | Subject and stimuli | Results |
|---|---|---|---|---|
| Effect of sensorineural hearing loss on cortical event related potential and behavioural measures of speech-sound processing | Oates, Peggy A Kurtzberg, Diane Stapells, David R | 2002 | CAEPs were obtained from 20 normal subjects and 20 adults suffering from hearing impairment towards /ba/ and /da/ speech stimuli delivered at two different intensities, 65 dB and 80 dB. Each stimulus was presented at oddball experimental paradigm and at both listening condition: active and passive. | CAEPs amplitudes for sensorineural hearing loss exhibited lower score compared to healthy subjects. In sensorineural hearing loss subjects, the latencies of CAEPs late components (N2/P3) and behavioural discrimination (d' and RT) were prolonged compared to the earlier components (N1/MMN) |
| Effects of sensorineural hearing loss and personal hearing Aids on cortical event-related potential and behavioural measures of speech-sound processing | Peggy A. Korczak, Diane Kurtzberg, and David R. Stapells | 2005 | CAEPs were obtained from 20 normal subjects and 14 adults suffering from hearing impairment towards /ba/ and /da/ speech stimuli delivered at two different intensities, 65 dB and 80 dB. | The application or usage of hearing aids enhance the detectability of all CAEPs components and behavioural d-prime score for both intensities. This is more applicable and clear finding experienced by individuals having sever-profound hearing losses. |
| P300 in subjects with hearing loss | Reis, Ana Cláudia Mirândola Barbosa Iório, Maria Cecília Martinelli | 2006 | CAEPs were recorded from 15 males and 14 females between 11 to 42 years old having severe-profound level SNHL | P300 was clearly showed in subjects with hearing loss (17 out of 29 subject). The mean amplitude was 3.76 µV and mean latency was 326.97 ms |

| Research title | Authors | Year | Subject and stimuli | Results |
|---|---|---|---|---|
| The use of cortical auditory evoked potentials to evaluate neural encoding of speech sounds in adults | Katrina Agung Suzanne C. Purdy Catherine M. McMahon | 2006 | CAEP waveform were recorded from 5 male adults and 5 female adults using speech vowels stimuli | There are some significant differences on the amplitudes of CAEPs components between high frequency energy compared to sounds dominated by lower-frequency energy. Greater amplitudes and earlier latencies were evidence in response to shorter duration stimuli compared to longer duration. |
| Effects of hearing aid amplification and stimulus intensity on cortical auditory evoked potentials | Curtis J. Billings Kelly L. Tremblay Pamela E. Souza Malcolm A. Binns | 2007 | Tone burst at 1000 Hz were presented to 13 adults with normal hearing sensitivity at 7 different stimulus level, at both condition; aided and unaided | No effect was found in response to CAEPs amplitudes. However, CAEPs latency were longer in aiding condition. |
| Effects of various articulatory features of speech on cortical event-related potentials and behavioural measures of speech-sound processing | Korczak, Peggy A Stapells, David R | 2010 | 20 adults with normal hearing level were presented with three sets of CV speech stimuli; /bi/ versus /bu/, /ba/ versus /da/, /da/ versus /ta/ delivered at two different intensities, 65 dB and 80 dB. Each stimulus was presented at oddball experimental paradigm and at both listening condition: 10 | Vowel contrast stimulus elicited higher CAEPs mean amplitudes compared to two consonant contrast. Shorter latencies on MMN, P3b and RT were found in responses to vowel contrast. On majority of CAEP components, only small nonsignificant differences occurred in either the CAEP amplitude or the latency response measurements for |

| Research title | Authors | Year | Subject and stimuli | Results |
|---|---|---|---|---|
| | | | individuals with active and 10 individuals with passive. | stimuli within a particular articulatory feature of speech. |
| Middle and late latency event related potential components discriminate between adults, typical children, and children with sensory processing disorders | Patricia L. Davies1, Wen-Pin Chang2 and William J. Gavin | 2010 | The study used two randomized tone burst stimuli, 1000 and 3000 Hz presented at two different intensities, 50 dB and 70 dB. CAEPs were recorded from three groups study; 1) 18 adults between 20-55 years 2) 25 typical children between 5-10 years 3) 28 children with sensory processing disorders (SPD) | CAEP components were clearly recorded for each auditory stimulus. Discriminant analyses revealed two functions, one which described the relationship of the components on SPD deficit continuum and one which described the relationship of these components on a developmental continuum. |
| Aided cortical auditory evoked potentials in response to changes in hearing aid gain | Curtis J. Billingsa, Kelly L. Tremblay, and Christi W. Miller | 2011 | CAEPs were obtained from nine individuals with normal hearing threshold in two different conditions; aided versus unaided. In the aided condition, a 40 dB signal was delivered using 0, 10, 20, and 30 dB. For control purpose, the unaided stimulus levels were matched to aided condition outputs | In the aided condition, CAEPs activation were extremely smaller and longer response timing compared to unaided. This finding might closely related to the noise levels produced by the hearing aid. |

| Research title | Authors | Year | Subject and stimuli | Results |
|---|---|---|---|---|
| | | | i.e., 40, 50, 60, and 70 dB | |
| Diminished N1 auditory evoked potentials to oddball stimuli in misophonia patients | Schröder, Arjan van Diepen, Rosanne Mazaheri, Ali Petropoulos Petalas, Diamantis de Amesti, Vicente Soto Vulink, Nienke Denys, Damiaan | 2014 | They aimed in proving the existence of brain's early auditory processing system in misophonia population. The study recruited 20 patients suffered from misophonia and 14 control healthy subjects. CAEPs were recorded in response to 250 Hz and 4000 Hz tone burst presented in oddball randomized paradigm embedded in stream if repeated 1000 Hz standard tones. | CAEP N1 components in misophonia showed smaller mean amplitude compared to control. There are no main effects revealed in response to oddball tones stimuli by P1 and P2. Attenuation on N1 components in misophonia condition suggest an underlying neuro-biological deficit and conclude that these finding might reflect the basic impairment in misophonia auditory processing disruption |

| Research title | Authors | Year | Subject and stimuli | Results |
|---|---|---|---|---|
| Task-dependent decoding of speaker and vowel identity from auditory cortical response patterns | Bonte, Milene Hausfeld, Lars Scharke, Wolfgang Valente, Giancarlo Formisano, Elia | 2014 | The current study used functional magnetic resonance imaging (fMRI) technique to understand the human auditory cortical response. Subjects were presented to the similar speech sounds (vowels /a/, /i/, and /u/) which were produced by different speakers and performed a delayed-match-to-sample task on either speech sound or speaker identity. | Univariate analyses showed increment in the task-specific activation at the right superior temporal gyrus/sulcus (STG/STS) during speaker categorization and in the right posterior temporal cortex during vowel categorization. Speaker/vowel classification relied on distinct but overlapping regions across the (right) mid-anterior STG/STS (speakers) and bilateral mid-posterior STG/STS (vowels), as well as the superior temporal plane including Heschl's gyrus/sulcus. |
| Distributed neural representation of phonological features during speech perception | Arsenault, Jessica S Buchsbaum, Bradley R | 2015 | fMRI techniques were used together with the multivoxel pattern analysis to determine the categorical and perceptual correlation of 16 different English consonants based on the pattern of neural distribution. | Bilateral primary, secondary and areas of superior temporal cortex were closely related with the categorical distribution involving features of voicing and manner articulation instead of motor cortex. They found multivariate pattern information was moderately stronger in the left hemisphere compared with the right hemisphere for placing contrast but not for voicing or manner of articulation. |

## 2.9 Novel contribution of the present dissertation

In our study, only two features of speech articulation were chosen which are voice/voiceless distinction and placing contrast of speech phonemes. As a continuation of previous studies, acoustic cues /ba/ and /da/ tokens which reflecting different place of speech articulation were selected since these features providing crucial CAEPs clinical application towards understanding the brain speech perception besides correlates with the peripheral hearing deficiency (Arsenault & Buchsbaum, 2015; Boothroyd, 1993; Korczak et al., 2005b; Korczak & Stapells, 2010; Oates et al., 2002b). The other features of speech articulation emphasized in this study is the voice/voiceless acoustic cues reflecting by the CV /ba/ and /pa/ tokens. In our current development, we made significant strides in an effort to evaluate the neurological changes in speech perception difficulties from normal as well people with sensorineural hearing deficit to impart new avenues for better hearing rehabilitation. Through this concept, a novel approach to understand the neural encoding deficiency on the multimodal hearing perception of CAEPs in SNHL individual could be analyzed.

The major aim of the current study was to employ the effects of CAEP components as a measure of voice/voiceless distinction against place of articulation involving CV stimuli during passive listening between healthy normal and individuals suffering from SNHL. Collectively, these electrophysiological measures may be well explained on the differences happened during preconscious speech processes at higher levels in the brain, besides revealed the direct relationship between the acoustic signal and the perceived phoneme (Abbs & Sussman, 1971; Stapells, 2002). We hypothesized that since these two sounds are phonetically and spectrally distinct, they may evoke CAEPs with different morphological responses and might provide us information on how auditory pathway performing discriminant mechanism during passive perception between each of these different speech sounds since the goal is to apply in everyday life. As per objective, the current study only included the native Malaysian Malay ethnic groups where Malay CV speech tokens were presented, and we hypothesized that the MMN will be elicited due to the present of language memory trace (Näätänen, 2001; Ylinen et al., 2006). This hypothesis supports the previous finding when the MMN were elicited in response to natural English and Finnish speech sound (Becker & Reinvang, 2007; Tampas et al., 2005).

# CHAPTER 3: METHODOLOGY

## 3.1 Participants

Two groups of subjects were recruited in the present study: 1) 12 adults' right-handed Malayan male subjects (fluent Malay-speakers) between 20 and 45 years of age having bilateral SNHL for more than 6 months (mean age=32.2 year, SD=6.9 year); and 2) 12 adults' right-handed Malayan male subjects (fluent Malay-speakers) between 20 and 45 years of age with normal hearing sensitivity (mean age=28.7 year, SD=5.4 year) served as a control group (NH). Normal hearing participants recruited were healthy normal with no past history of otological, psychological or neurological complications and without speech or hearing disorders. All participants involved in this study were tested by Otorhinolaryngology (ENT) department in University Malaya Medical Centre (UMMC) using routine pure tone audiometry (PTA) measurement (Association, 2005)(Appendices B and C). Written informed consent was obtained from all participants (Appendix E). The study was approved by the Medical Ethics committee, University of Malaya Medical Centre (Reference No. 1045.22) (Appendix A). In the present study, only righthandedness was recruited to prevent any brain lateralization, since right handed people will have left hemispheric language specialization as supported by some of the previous researchers (Annett, 1975; Kavaklioglu et al., 2017; Medland et al., 2009). Summarization of the experimental procedures done throughout the entire study was illustrated in Figure 3.2.

Figure 3.1: SNHL patient participation for EEG data recording.

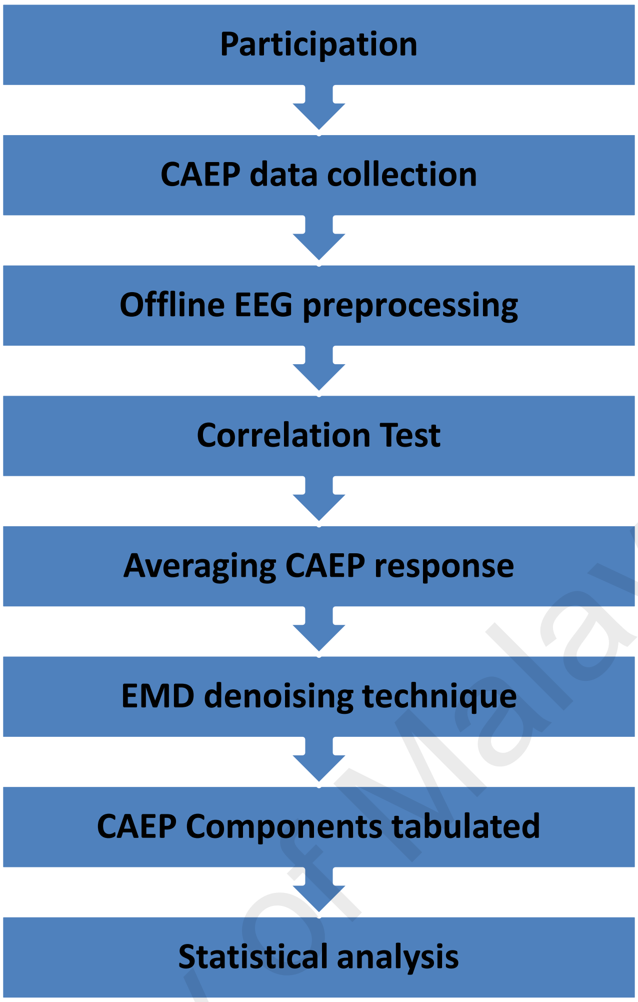


Figure 3.2: Summarized of CAEP process flowchart for data analysis.

The normal hearing (NH) subjects showed normal pure-tone audiological presentation of 15 dB hearing level (HL) or better between 250 to 8000 Hz on both ears. The participants enrolled in the hearing problem (SNHL) group ranging from mild to moderate hearing loss level bilaterally based on the average of their 500 Hz to 2000 Hz pure-tone thresholds (PTA ≥ 35 dB HL and PTA< 70 dB HL). Additional criteria for all the participants included no exposure to ototoxic drugs and were native speaking individuals of Malay language. The details of the participant profile where shown in Table 3.1. To evaluate the cognitive state, attention, mental and memory capabilities, and language deprivation of selected participants, a simple Mini Mental State Examination (MMSE) was conducted before the recording session (Folstein, Folstein, & McHugh, 1975)(Appendix F). In this test, they were given with 30 questionnaires and they were selected if they score is at least 27 marks and above (score ≥ 27). The result of MMSE scores for all the volunteers are demonstrated in Table 3.2.

Table 3.1: Profile of participants

| Subjects | No. of Subjects | Age | Gender | Handedness |
|---|---|---|---|---|
| Normal hearing (NH) | 12 | Mean=26.83, SD=3.94 | M | Right |
| Sensorineural hearing loss (SNHL) | 12 | Mean=38.71, SD=7.87 | M | Right |

Table 3.2: MMSE scores of NH and SNHL subjects

| NH | MMSE Score | SNHL | MMSE Score |
|---|---|---|---|
| NH001 | 30 | SNHL001 | 30 |
| NH002 | 30 | SNHL002 | 28 |
| NH003 | 30 | SNHL003 | 30 |
| NH004 | 30 | SNHL004 | 30 |
| NH005 | 30 | SNHL005 | 30 |
| NH006 | 30 | SNHL006 | 30 |
| NH007 | 30 | SNHL007 | 30 |
| NH008 | 30 | SNHL008 | 29 |
| NH009 | 30 | SNHL009 | 30 |
| NH010 | 30 | SNHL010 | 29 |
| NH011 | 30 | SNHL011 | 30 |
| NH012 | 30 | SNHL012 | 28 |

## 3.2 Stimulus presentation

The study selected two different sets of speech articulation features differed by one phoneme which are voice/voiceless distinction *ba* versus *da* (/ba-da/) and place of articulation property *ba* versus *pa* (/ba-pa/) characterized by CV speech stimuli respectively presented at 80 dB sound pressure level (SPL) to satisfy both degree of SNHL presents in the current study (Association, 2005; Dehaene-Lambertz & Baillet, 1998; Korczak & Stapells, 2010; Ladefoged & Maddieson, 1998; Wunderlich & Cone-Wesson, 2001). We ensure that the selected intensity level was loud enough in each volunteer and delivered at the most comfortable listening level. The two specific articulatory speech features (voice/voiceless distinction and placing contrast) were selected for their specific purposes. A placing contrast features of the stop consonant (/ba-da/) was chosen because this is an articulatory features of speech that is specifically liable to the impact of peripheral hearing-impaired individuals, in the fact that CAEP could be used to perform speech perception abilities in future clinical application within this target population (Boothroyd, 1993). The speech confusion in hearing loss people happens mainly between stop consonants that differ with place of articulation. This means that the phonologic cues that signal from place of articulation tend to be specifically vulnerable when auditory processing stop working (Boothroyd, 1993; Martin & Boothroyd, 2000). Secondly, the phonologic features related to voiced/voiceless discrimination were chosen due to the sensitivity and specificity of CAEP response to the changes in voicing, as evidence in several previous studies when poorly perceptual were assessed in longer time-varying speech stimuli (Korczak et al., 2005b; Sharma et al., 2000; Tremblay, Piskosz, et al., 2003). The stimulus presentation is summarized in Table 3.3. The natural digitizing speech tokens were produced by a female Malayan Malay native speaker and recorded at 44,100 Hz using unidirectional microphone placed approximately fifteen centimeters from the speaker's mouth in a sound proof chamber.

The tokens were edited into 250 ms in duration by removing the vibration of the vocal cord portion, the end part of the steady state vowel and windowing the offset. Different durations of naturally produced CV speech stimuli were used in many literature, ranging from 90-600 ms (Korpilahti, Krause, Holopainen, & Lang, 2001; Obleser, Eulitz, Lahiri, & Elbert, 2001; Sharma et al., 2000). Aforementioned, the variation in the stimulus duration may not give much effects towards CAEP signals as long as enough time were given to develop afferent processes and for the consecutive temporal and features integration of human auditory system. Data obtained from Rosburg, Haueisen, and Sauer (2002) showed that the CV duration did not effect on the activation of CAEP as well as the latency responses when dealing with up to 400 ms stimuli. Consequently, several

MMN studies highlighted on the sufficient stimulus duration in order to achieve adequate MMN response (Duncan et al., 2009; Näätänen, 2008). The stimulation period was suggested to be between 150 ms-350 ms, however these durational differences are linked to the matching interstimulus-interval (ISI) duration and preferred number of deviant types (Duncan et al., 2009; Maiste, Wiens, Hunt, Scherg, & Picton, 1995; Picton et al., 2000; Steinhauer, 2014). The present work used 250 ms CV stimuli with the matching ISI which were set between 600 ms to 1000 ms (3 to 4 times greater that the stimulus duration) as suggested by most of review studies. One study done by Maiste et al. (1995) used CV speech stimuli with 350 ms and the ISI was set within the range of 1000 ms - 1400 ms to ensure that the brain may have sufficient timing when performing categorical phonemes. However, there seems to be no solid agreement done emphasizing about the optimal speech stimulus duration in evaluating CAEPs responses.

Table 3.3: Selected articulatory phonetics features and descriptions of CV tokens

| Speech Features | Features' Description | Categories | Consonant selection | Vowel selection (fixed) | Consonant-vowel (CV) Tokens |
|---|---|---|---|---|---|
| **Voicing** | The existence of vocal cords vibration during articulation | Voiced bilabial stop | /b/ | /a/ | /ba/ |
| | | Voiceless bilabial stop | /p/ | /a/ | /pa/ |
| **Place of articulation** | The significant blockage occurrence in the vocal tract during articulatory gesture | Voiced bilabial stop | /b/ | /a/ | /ba/ |
| | | Voiced alveolar stop | /d/ | /a/ | /da/ |

The CVs stimulus was played at pseudorandomized oddball paradigm consisted of standard stimuli having 0.8 occurrence probability and the deviant stimuli occurred in 0.2 of presentations tested for two successive runs with a few minutes of rest between runs. For each set of speech stimuli, both CVs sounds were presented as standards and deviants in separate runs with onset inter-stimulus intervals (ISI) of 800±200 ms duration and delivered monaurally via Sennheiser HD 428 closed circumaural headphones to both ears as visualized in Figure 3.3. This randomized slight onset interval reduces the temporal prediction probability of the incoming auditory stimulus for both standard and deviant stimuli. The stimulus presented were calibrated at ear level using CR:160 series Cirrus Optimus red sound level meter to obtain the desired SPL level (Anderson et al., 2013; Billings et al., 2007) (Appendix G). In each run, the speech CVs tokens consisted of 400 total stimuli; i.e. 320 standard stimuli and 80 deviant stimuli, in such conditions that 2-6 standard stimuli were presented between each deviant stimulus. Thus, each stimulus contrasts yielding a total of 800 stimuli containing 160 deviant stimuli and 640 standard stimuli replicated over the two runs. Counterbalanced paradigm was implemented in this study where one token act once as a deviant in one run and once as standard in another run for each set of CVs stimuli respectively, i.e., for /ba-da/ stimulus, /ba/ stimulus will act as a standard first and as deviant later in a single run for each experimental group, followed by /ba-pa/ stimulus as well (Duncan et al., 2009; Korczak & Stapells, 2010).

Figure 3.3: Sennheiser HD 428 closed circumaural headphones.

The time domain waveform and spectrographic analysis of the CVs stimulus in Figure 3.4 illustrated the formant and pitch frequencies along 250 ms duration produced by the phonetic analysis software Praat 5.4.18 (Boersma & Weenink, 2015). Spectrogram analysis devote on the spectro-temporal features of the speech stimuli, outlining two distinct regions of energy density. The initial time window of CVs /ba/ and /da/ stimulus visualized lighter region indicated lower energy densities compared to the late window, contrary to CV /pa/ stimulus which encounter higher energy densities during the early time window so as to assert the 'voiced' and 'voiceless' characteristics of these consonants during articulatory gesture. The types of articulatory phonetics features are classified based on the nature constriction factor of air in the vocal tract which determined the acoustical qualities of the consonant (Arsenault & Buchsbaum, 2015; Gordon-Salant, 2014; Jaramillo et al., 2001; Ting et al., 2011), thus emphasizing the contradict perspective of the respective CVs stimuli highlighted in the current study.

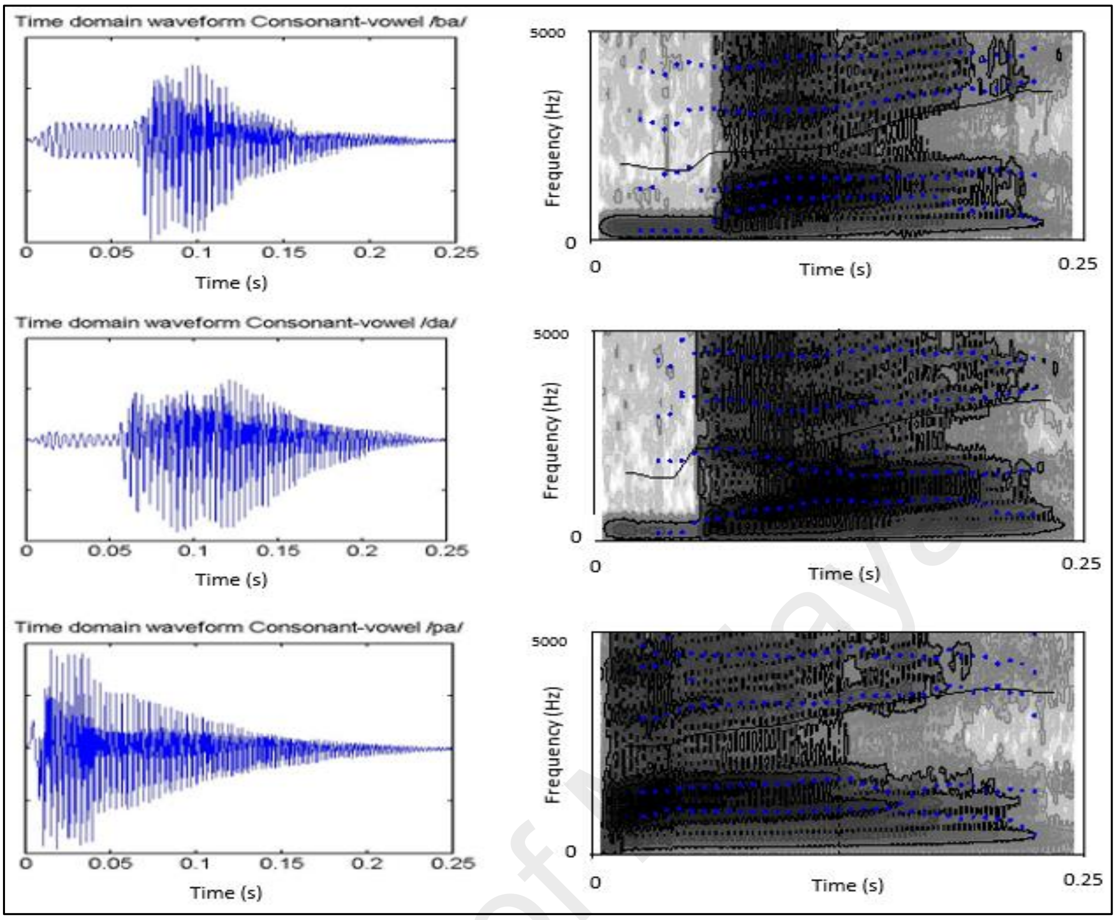


Figure 3.4: Consonant-vowel stimuli. Left: Time domain waveform of speech cues presented at 80 dB SPL (250 ms). Right: Spectrograms of speech stimuli. The bold solid and dotted line represents the sound's pitch and formant contour respectively. Formant frequencies (Hz) were /ba/: F0 292, F1 740, F2 1481, F3 3228, F4 4310, /da/: F0 291, F1 928, F2 1523, F3 3155, F4 4254, /pa/: F0 344, F1 759, F2 1795, F3 3478, F4 4437.

## 3.3 Electrophysiological cortical auditory evoked potential (CAEP) recordings

The electroencephalography activity of the CAEPs was recorded at 500 Hz sampling frequency from eight EEG electrode channels with a wireless EEG device system (EnoBio 8, Neuroelectrics, Spain)(Ruffini et al., 2007; Ruffini et al., 2006) using Ag/AgCl electrodes mounted on the Neoprene EEG cap as shown in Figure 3.5. A standard computer equipped with Neuroelectrics NIC 1.3 software (EEG data collection) and MATLAB R2013a (stimulus presentation and analysis) software were designed and used for the electroencephalographic data collection and post-processing analysis. Electrodes were placed at $F_Z$, $C_Z$, $P_Z$, $F_7$, $T_3$, $C_3$, $T_5$, and $F_{PZ}$ as presented in Figure 3.6. These electrodes placement were selected based on the optimum brain responses towards selective hearing and processing language or speech comprehension (Bley-Vroman, 1989; Danermark, Manchaiah, Rönnberg, & Lunner, 2014; Maiste et al., 1995). The active Common Mode Sense (CMS) electrode served as referenced and passive Driven Right Leg (DRL) electrode served as ground were both connected to two electrodes located at the right mastoid.


Figure 3.5: Enobio 8 Wireless EEG device and Neuroelectics NIC 1.3 software for EEG data recording (Ruffini et al., 2007; Ruffini et al., 2006) (Adapted from http://www.neuroelectrics.com/).

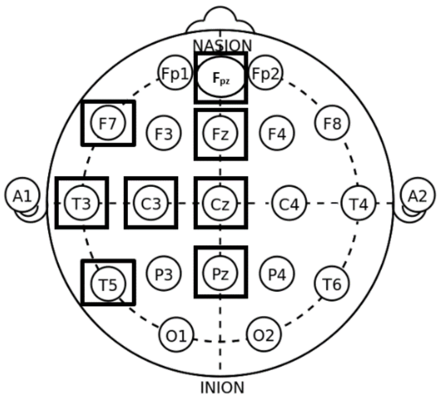


Figure 3.6: Electrophysiological montage placement (square bold) according to International 10/20 System (Adapted from http://www.ebme.co.uk/articles/clinical-engineering).

All the participants were instructed to sit quietly and comfortably in a sound proof chamber as illustrated in Figure 3.7. Prior to electrophysiological recording, all the subjects were practiced to reduce the eye blinks and muscle movement artifacts to obtain data optimization. Since the study involved passive listening conditions, all the volunteer was trained to ignore the incoming auditory stimuli, stay awake and focused on the Malay reading materials provided to them. All testing procedure was done with two successive runs within each set of experiment with an approximation of 50 minutes per run. They were permitted to get up and stretch (without removing or altering the electrode cap) between each set of experiment to maintain an awake and energized state.

Figure 3.7: Sound proof chamber for EEG data recording.



## 3.4 CAEP waveform measurement and data analysis

On the completion of CAEP data recording from all volunteers, the evoked response first went through the offline pre-processing techniques (artifacts rejection, baseline drift correction and power supply filtering). These processes were done using notch filter at 50 Hz and Butterworth band-pass filter between the frequency domains 1-45 Hz. This filter setting can vary depending on which CAEP components area of interest. In the present study, we are focused on five major CAEP components which are P1, N1, P2, N2 and P3. Based on the literature review, due to the fact that the current study compared the patient with control, it is advisable to have filtering setting in higher bandwidth range. Thus, the optimum frequency bandwidth in assessing all these components was set between 1-45 Hz (Duncan et al., 2009; Picton et al., 2000).

For each set of experiment, the two successive runs of each group standard and deviant stimuli were averaged. Due to the implementation of the counterbalance paradigm in this study, the evoked response obtained from the counterbalance standard and deviant stimuli were summed with the previous session and averaged. Finally, each set of stimulus presentation will produce an evoked response classified as "standard" and "deviant" stimulus and grouped separately. The standard average response to the stimulus which appeared immediately after the deviant stimulus was excluded. The N1 and N2 components were identified as the most negative peak occurred between 80–150 ms and 180–250 ms immediately after the stimulus onset respectively. P1 and P2 were defined as the most positive deflection happened between 55–80 ms and 145–180 ms post-stimulus onset respectively. P3 was scored between 220–380 ms, illustrated by the most positive peak appeared after the stimulus onset within this response window. Originally, the standard and the deviant stimulus undergo de-noised process using empirical mode decomposition (EMD) technique (Blanco-Velasco, Weng, & Barner, 2008). Figure 3.8 illustrated the cleaned standard and deviant waveform response towards CVs stimulus before and after the implementation of EMD filtering mode.

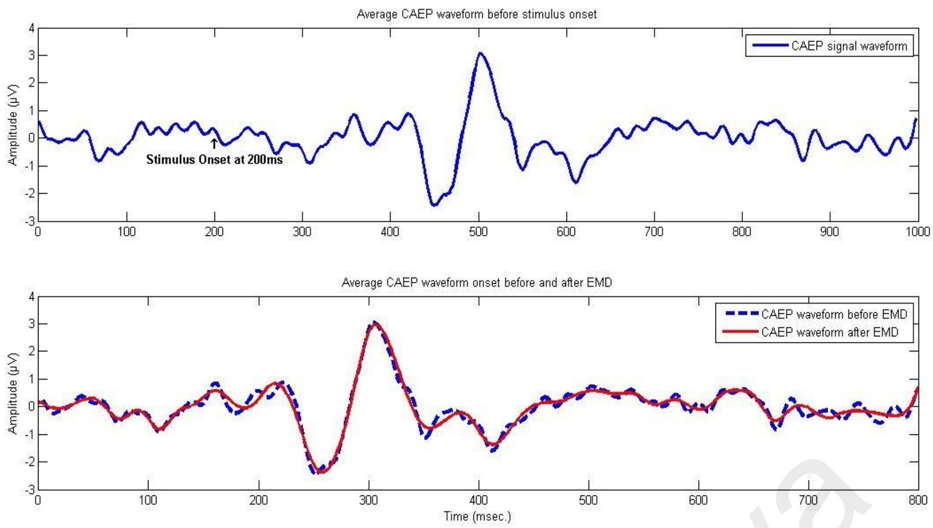


Figure 3.8: CAEP waveform recorded before and after EMD de-noising process. The top row of waveforms (before EMD de-noising) showed the stimulus onset position presented at 200 ms throughout the recording session. The bottom row of waveforms is the cleaned CAEP waveform before and after EMD filtering takes at 800 ms duration after stimulus onset.

The rules used to justify the existence or absence of a response in the passive condition were as follows: (1) CAEP was inspected visually by two raters and considered to be present if an individual CAEP peak (e.g. P1, N1, P2, N2, MMN, and P3) having higher amplitude than the prestimulus baseline level; and (2) Inspected quantitatively using statistical analyses (i.e., correlation coefficient test, *p* value and two-way repeated measure ANOVA) involving baseline peak-to-peak amplitude and latency comparison with the standard typical CAEP waveform described by previous findings (Näätänen, 1992; Rotteveel, 1990); to be considered present if an individual's CAEP components having maximum correlation coefficient (r) and significant value ($p < 0.05$).

The CAEP difference waveform for each set of speech stimulus used to measure the MMN response were obtained by subtracting the averaged responses to the deviant stimuli with the averaged responses to the same stimuli presented as standard, thus controlling for speech feature differences. MMN was defined as a component having the largest negativity occurring between 100-250 ms at Fz or Cz in the different waveform which able to provide valid objective in understanding the accuracy of central auditory processing in human brain especially during phonological features discrimination for various clinical applied purpose (Duncan et al., 2009). The appearance of MMN was confirmed when it has more negative amplitudes at the fronto-central electrode site (e.g. Fz and Cz) in comparison with the parietal site (e.g. Pz) based on polarity inversion at the mastoid electrode sites, however the response present was not criticized due to the inversion deficiency. The amplitude evoked responses were compared with the prestimulus baseline and measured as the greatest amplitude recorded followed by the latency measurements taken at the center of the peak obtained within the respective response window. Duplications were averaged together for each set of stimuli (Duncan et al., 2009; Oates et al., 2002b). The late CAEP amplitude and latency components were recorded from each individual response windows to develop the grand-mean-waveforms for each CVs stimulus (i.e. /ba-da/ and /ba-pa/) respectively as per the two types of experimental groups (i.e. normal hearing (NH) and sensorineural hearing loss (SNHL)). The amplitudes and latencies of various CAEP components were then assessed independently between hearing impaired subjects (SNHL) and controls as “standard” and “deviant” stimulus.

## 3.5 Statistical analysis

The independent t-test initially was done at the age between the participants involved to make sure no other factors might contribute to the main finding of the study. The CAEPs were analysed using descriptive statistical measurement, correlation coefficient test, and the final response were analysed using two-way repeated measures analysis of variance (ANOVAs) technique using IBM SPSS Statistics 23.0 software. The study involved two stages of correlation coefficient test. Initially, each of individual's responses was compared with the previous study and the standard typical CAEP waveform (Carballo-gonzalez, Valdes-sosa, & Valdes-sosa, 1989; Korczak et al., 2005b; Korczak & Stapells, 2010; Näätänen, 1992; Rotteveel, 1990; Wunderlich & Cone-Wesson, 2001). Individual response having a maximum positive correlation coefficient ($r^2 = 0.825$) with the standard waveform was then selected as the typical standard trend CAEP waveform for the present study. Second stages were done between the rests of the individual subject's responses with the current typical waveform. Individual's responses having maximum correlation and significant value ($P < 0.05$) were accepted and those having low correlation and $P$ value were neglected for further analysis. The CAEPs amplitudes and latencies were then analysed individually using two-way repeated measures ANOVA to identify the correlation dependence of the CAEPs components on each set of speech stimuli and their relationship between both phonetics features. The two factors highlighted in the ANOVAs were as follows; (1) speech stimuli /ba-da/ and (2) speech stimulus /ba-pa/. Main effects and interaction with the CAEPs component were considered significant if $p < 0.05$. The selection of these factors are able to hypothesized if there is any significant difference on the CAEPs components based on two types of speech stimuli and the interaction among them between both study groups.

# CHAPTER 4: RESULTS

## 4.1 De-noising: Empirical mode decomposition (EMD)

As mentioned in the methodology section, the averaged standard and deviant responses were initially de-noised using EMD techniques. Figure 4.1 displayed the individual sample result of average CAEPs waveforms after EMD filtering for control subject 1 and SNHL subject 1 in response to each set of speech stimuli after stimulus onset.

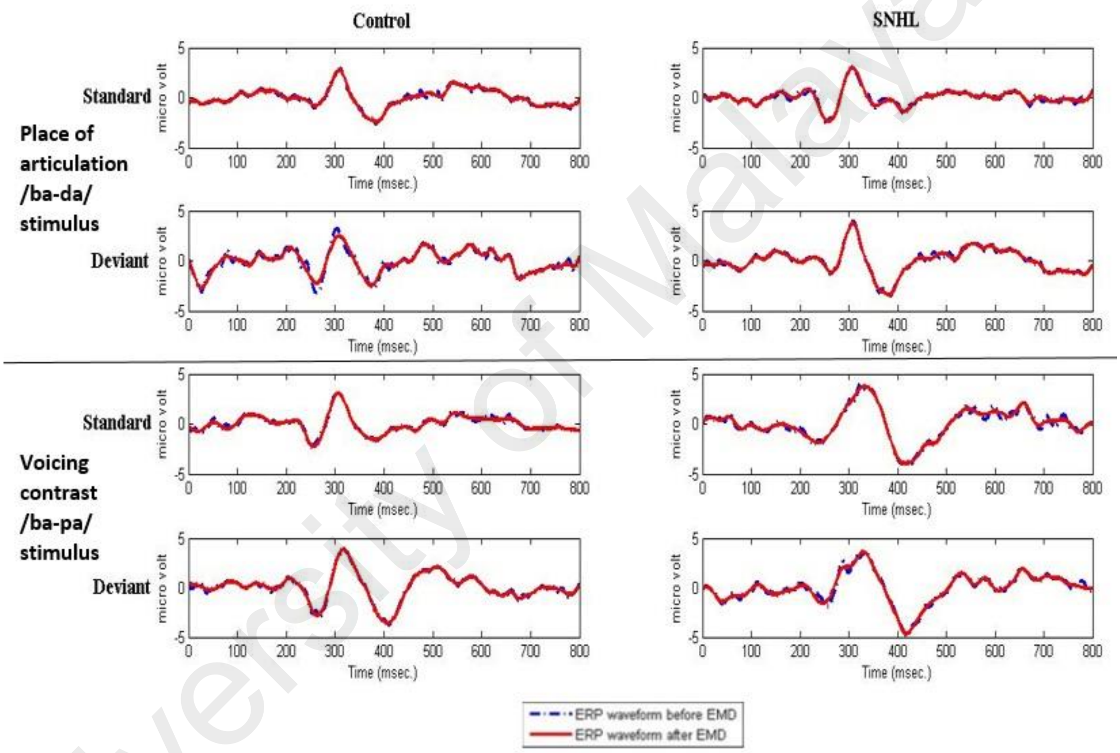


Figure 4.1: Individual sample average CAEPs waveform after EMD filtering [control subject 1 and SNHL subject 1]. The top row waveform illustrated CAEPs responses on speech of articulation for both standard and deviant stimuli. The bottom row displayed the CAEPs responses for both standard and deviant on voicing contrast stimuli.

## 4.2 CAEPs amplitudes and latencies responses

Figure 4.2 demonstrated a sample of individual control group contrast responses towards both sets of speech stimulus. This control subject's response explained the common trends found in the average CAEPs waveform. Typically, as referred to Figure

4.2, CAEP mean amplitudes exhibit higher activation in the deviant stimulus compared to the standard stimulus for both speech conditions. The CAEP latencies for the place of articulation are substantially shorter and produced lower activation than the voicing contrasts.

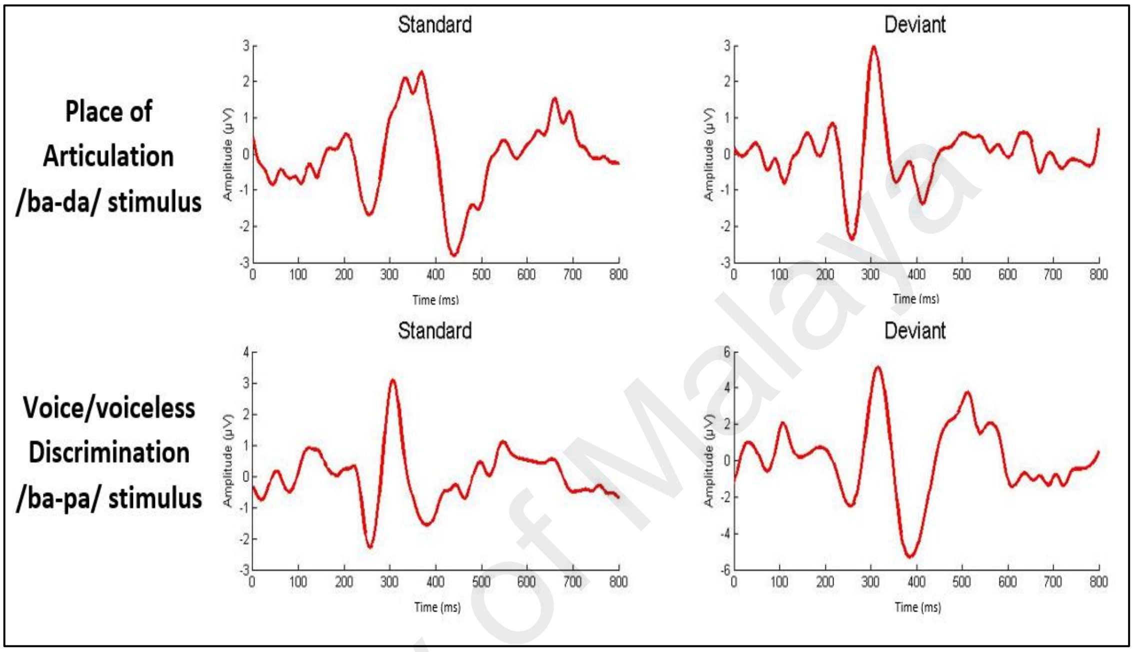


Figure 4.2: Average CAEPs waveforms (Cz) recorded from control subject 1. The top row waveforms represented the averaged standard and deviant stimulus responses to the place of articulation /ba-da/ stimuli. The bottom row waveforms showed the averaged standard and deviant stimulus responses to the voicing contrast /ba-pa/ stimuli.

As is evident in Figure 4.3, there was a trend for both speech stimuli recorded from patient's CAEPs response as well in difference waveforms. Apparently, the deviant stimulus demonstrated higher amplitude and shorter latency compared to the standard type of the placing contrast stimulus in exception was voicing contrast stimulus which showed opposite pattern of response. Based on the MMN waveform, higher negativity response and longer latency presented from the feedback towards voicing contrast in comparison with the placing contrast stimulus.

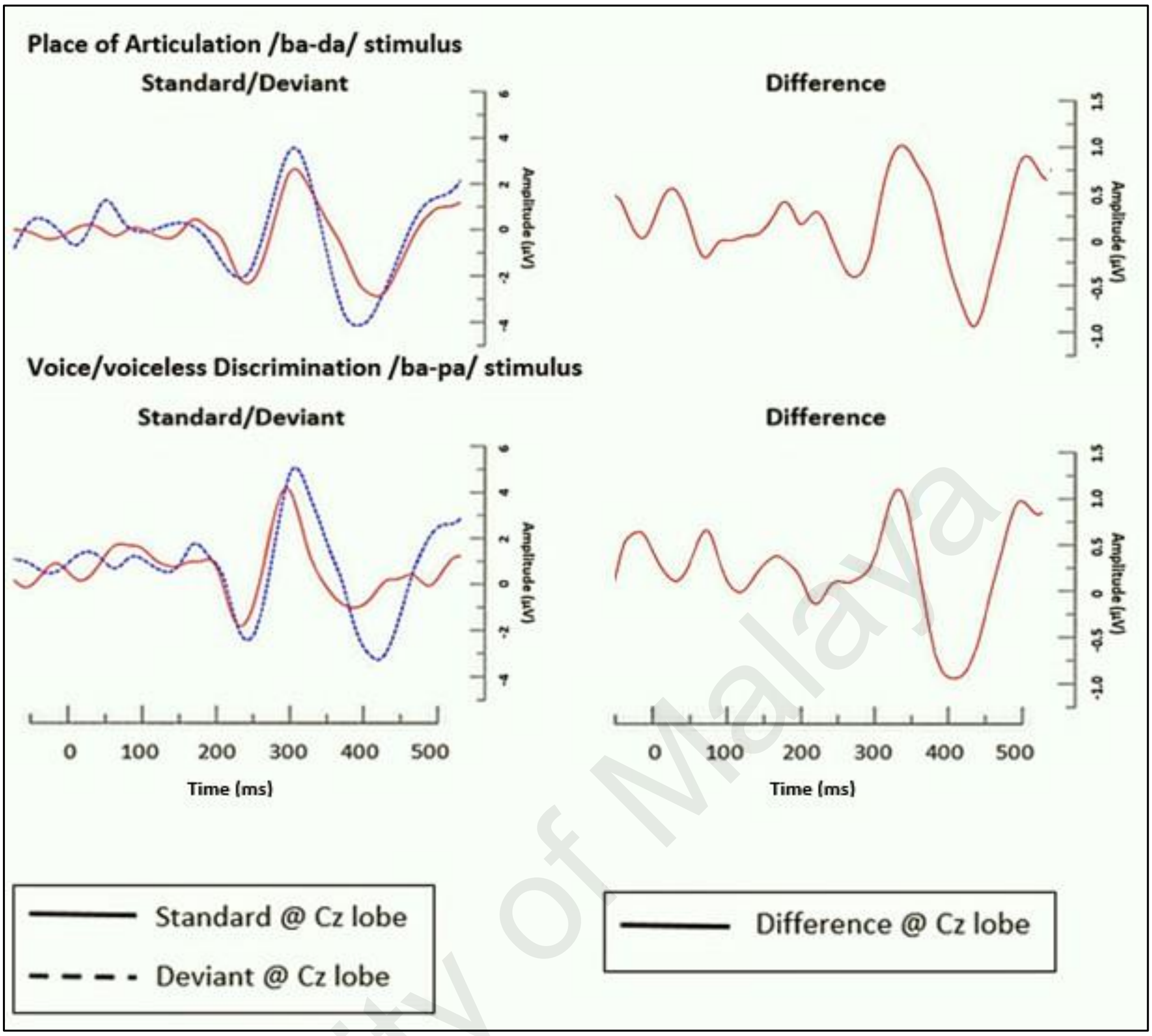


Figure 4.3: Average CAEPs waveforms recoded from SNHL subject 1. The top row illustrated the CAEP waveform response to the place of articulation stimuli and the difference waveform recorded at Cz. The bottom row is CAEP waveform response to the voicing contrast stimuli and difference waveform recorded at Cz.

Table 4.1 and Figure 4.4 indicates the average mean and standard deviation (SD) correspond to the effects of both articulatory features of speech on the amplitudes of the CAEPs waveform recorded at Cz electrode. The results of CAEPs testing revealed that all average deviant responds produced higher amplitudes activation in accordance with both sets of speech stimulus. P1 amplitude of SNHL population was larger in response to voicing contrast stimulus in comparison with the control subject. The only exception to this data was for P2 component when it showed reverse pattern of response.

Table 4.1: Mean and SD values on amplitudes of CAEPs components and mismatch negativity (MMN) across two types of speech contrast: /ba-da/ and /ba-pa/ between control and SNHL groups presented at 80 dB SPL (Cz)

| | /Ba-Da/ Speech Stimulus | | | | /Ba-Pa/ Speech Stimulus | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Control (N=12) | SNHL (N=12) | | | Control (N=12) | SNHL (N=12) |
| **P1 amp (μv)** | Stand | Mean | 0.29 | 0.66 | Stand | Mean | 0.75 | 0.81 |
| | | SD | 0.17 | 0.45 | | SD | 0.53 | 0.60 |
| | Dev | Mean | 0.63 | 1.12 | Dev | Mean | 1.16 | 1.28 |
| | | SD | 0.35 | 0.45 | | SD | 0.44 | 0.56 |
| **N1 amp (μv)** | Stand | Mean | -1.03 | -1.00 | Stand | Mean | -0.94 | -0.86 |
| | | SD | 0.36 | 0.33 | | SD | 0.37 | 0.36 |
| | Dev | Mean | -1.13 | -1.04 | Dev | Mean | -0.82 | -0.84 |
| | | SD | 0.43 | 0.64 | | SD | 0.40 | 0.68 |
| **P2 amp (μv)** | Stand | Mean | 0.48 | 0.59 | Stand | Mean | 0.39 | 0.37 |
| | | SD | 0.38 | 0.33 | | SD | 0.15 | 0.12 |
| | Dev | Mean | 1.19 | 0.69 | Dev | Mean | 1.27 | 1.24 |
| | | SD | 0.84 | 0.45 | | SD | 0.79 | 0.50 |
| **N2 amp (μv)** | Stand | Mean | -1.18 | -1.12 | Stand | Mean | -1.77 | -1.73 |
| | | SD | 0.50 | 0.66 | | SD | 1.10 | 1.06 |
| | Dev | Mean | -1.31 | -1.13 | Dev | Mean | -2.15 | -1.94 |
| | | SD | 0.47 | 0.68 | | SD | 0.92 | 1.15 |
| **P3 amp (μv)** | Stand | Mean | 2.79 | 2.93 | Stand | Mean | 3.12 | 3.34 |
| | | SD | 0.83 | 1.20 | | SD | 1.50 | 1.53 |
| | Dev | Mean | 3.21 | 3.78 | Dev | Mean | 4.02 | 4.19 |
| | | SD | 1.04 | 0.96 | | SD | 1.66 | 1.96 |
| **MMN (μv)** | Peak amp | Mean | -1.52 | -0.58 | Peak amp | Mean | -1.89 | -0.92 |
| | | SD | 0.46 | 0.25 | | SD | 0.83 | 0.32 |

Two conclusions may be drawn from the result stated above. First, the deviant response elicited higher neuronal activation experienced in both speech stimuli. It is evidenced that the higher evoked responses were recorded when the brain perceiving voicing contrast stimulus instead of placing contrast stimulus. This is true for the subjects with normal hearing as well as for those with SNHL. In general majority of the CAEP components elicited higher activation especially in voicing contrast stimulus. A second finding is that SNHL has a clear effect on these CAEP measures, as reflected by higher activation amplitudes recorded compared to normal hearing group. This is particularly evident in each component except for P2. The huge range of amplitude values in the normal hearing group causing the difficulty to the hearing-impaired groups to reinstate the desired activation for speech sound detection, thus resulting plausible disruption to the neuronal evoked response.

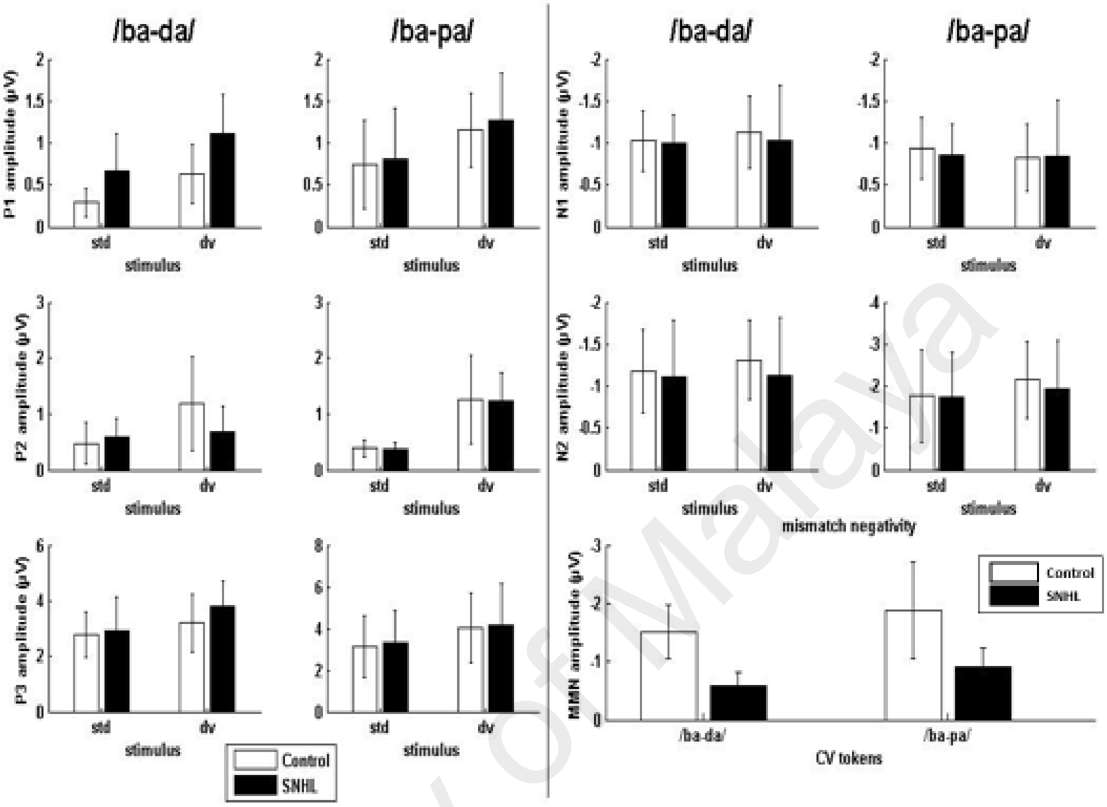


Figure 4.4: Mean and SD amplitudes for both control and SNHL groups across two types of speech stimuli presented at 80 dB SPL. Sample size in N=12 for each condition.

Table 4.2 indicate the mean and standard deviation (SD) measurements to the effects of both articulatory features of speech on the amplitudes and latencies of the CAEPs waveform at Cz electrode. P1 component experienced shorter timing response in /ba-pa/ stimulus at both groups study but the same response was revealed by P2 component in /ba-da/ stimulus. N1 and N2 components having similarity when both evoked longer average latencies in response to voicing contrast compared to the place of articulation stimulus. Figure 5 displayed the individual's data distribution of CAEP P3 components in response to both speech stimuli. Based on scatterplots in Figure 4.5, it is clearly recorded that the delayed and greater response of SNHL group towards voicing contrast stimulus. The deviant response on each set of stimuli showed contradict trend when it recorded at higher latency and greater amplitude during voicing contrast stimulus but happened at earlier response timing with the same pattern of neuron activation in placing contrast stimulus, and these were true for both SNHL and normal hearing groups.

Table 4.2: Mean and SD values on latencies of CAEPs components and mismatch negativity (MMN) across two types of speech contrast: /ba-da/ and /ba-pa/ between control and SNHL groups presented at 80 dB SPL (Cz)

| | /Ba-Da/ Speech Stimulus | | | | /Ba-Pa/ Speech Stimulus | | | |
|---|---|---|---|---|---|---|---|---|
| | | | **Control (N=12)** | **SNHL (N=12)** | | | **Control (N=12)** | **SNHL (N=12)** |
| **P1 lat (ms)** | Stand | Mean | 71.06 | 74.78 | Stand | Mean | 68.56 | 69.65 |
| | | SD | 9.38 | 8.12 | | SD | 7.75 | 5.94 |
| | Dev | Mean | 77.50 | 78.29 | Dev | Mean | 68.05 | 70.33 |
| | | SD | 8.98 | 5.11 | | SD | 6.52 | 5.55 |
| **N1 lat (ms)** | Stand | Mean | 108.95 | 119.28 | Stand | Mean | 114.40 | 129.44 |
| | | SD | 13.32 | 8.15 | | SD | 10.65 | 10.61 |
| | Dev | Mean | 111.85 | 126.20 | Dev | Mean | 122.75 | 134.50 |
| | | SD | 10.35 | 12.10 | | SD | 14.52 | 6.73 |
| **P2 lat (ms)** | Stand | Mean | 165.75 | 160.61 | Stand | Mean | 166.30 | 170.55 |
| | | SD | 6.47 | 6.88 | | SD | 8.11 | 8.13 |
| | Dev | Mean | 164.20 | 168.06 | Dev | Mean | 169.90 | 167.33 |
| | | SD | 7.71 | 5.18 | | SD | 10.13 | 8.16 |
| **N2 lat (ms)** | Stand | Mean | 204.30 | 232.11 | Stand | Mean | 220.15 | 240.65 |
| | | SD | 19.26 | 12.77 | | SD | 11.25 | 15.52 |
| | Dev | Mean | 217.85 | 234.89 | Dev | Mean | 226.05 | 240.00 |
| | | SD | 8.27 | 10.45 | | SD | 14.29 | 6.22 |
| **P3 lat (ms)** | Stand | Mean | 315.35 | 345.00 | Stand | Mean | 317.00 | 360.65 |
| | | SD | 19.52 | 16.90 | | SD | 12.13 | 18.57 |
| | Dev | Mean | 321.85 | 348.35 | Dev | Mean | 324.3 | 368.95 |
| | | SD | 17.87 | 17.48 | | SD | 8.20 | 21.73 |
| **MMN (ms)** | Peak lat | Mean | 187.30 | 201.23 | Peak lat | Mean | 190.91 | 215.74 |
| | | SD | 25.76 | 22.46 | | SD | 23.14 | 22.06 |

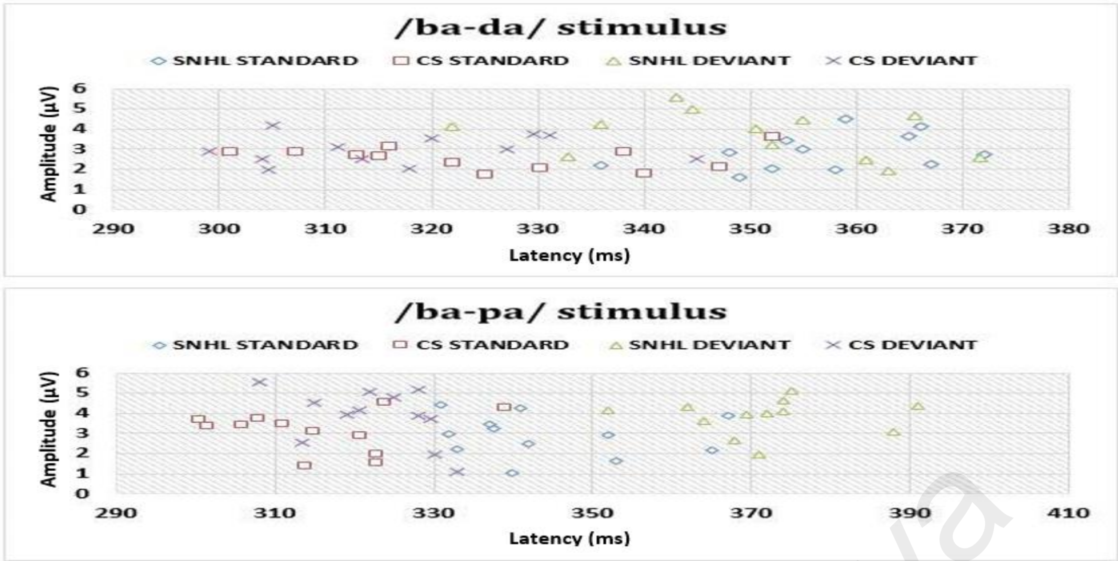


Figure 4.5: Amplitude and latency plots for P3 component showing differences between sets of speech stimuli, types of stimuli and study groups. Scatterplots demonstrate individual amplitude and latency values for P300 component.

### 4.3 Statistical analysis

The result of two-way repeated measures ANOVA were shown in Table 4.3. Primarily, we found that, there are no significant differences in the average CAEPs amplitude and latency between the response elicited by the standard and deviant stimuli. Evidences found in both experimental groups with both sets of stimuli; therefore, both types of stimuli were averaged together for that particular articulatory feature to find any significant difference on CAEP components between groups' response on both speech stimuli. The result of the ANOVAs outlined a significant effect for /ba-da/ stimuli on P1, N1 and MMN amplitudes as written in 'bold' text. The results of the ANOVAs reported a significant main effect was found on the P1 amplitude in response to place of articulation between groups [$p < 0.001$]. No significant difference for P1 component in response to voicing contrast stimulus and there is no significant interaction between both set of speech stimulus [$p = 0.135$ and $p = 0.406$].

Table 4.3: Results of two-way repeated measure ANOVAs on amplitudes and latencies of CAEP components between both speech stimuli

| ***Speech Stimuli*** | **Effect of speech features of articulation** | | **Effect of interaction** |
|---|---|---|---|
| | */ba-da/ stimulus (BD)* | */ba-pa/ stimulus (BP)* | *BD × BP* |
| | *Amplitude* | | |
| *P1* | **<0.001** | 0.135 | 0.406 |
| *N1* | **<0.001** | **0.015** | 0.075 |
| *P2* | 0.405 | 0.231 | 0.336 |
| *N2* | 0.690 | 0.989 | 0.837 |
| *P3* | **<0.001** | **0.029** | **0.042** |
| *MMN* | **0.036** | 0.941 | 0.379 |
| | *Latency* | | |
| *P1* | 0.563 | 0.703 | 0.961 |
| *N1* | **0.006** | **0.005** | **0.038** |
| *P2* | 0.772 | 0.713 | 0.558 |
| *N2* | 0.624 | 0.812 | 0.349 |
| *P3* | **<0.001** | **0.001** | **0.003** |
| *MMN* | **0.004** | 0.196 | 0.076 |

Both N1 and P3 amplitudes and latencies showed a significant main effect on both speech phonological features between control and SNHL groups [N1: $p < 0.001$ vs $p = 0.015$, $p = 0.006$ vs $p < 0.005$; P3: $p < 0.001$ vs $p = 0.029$, $p < 0.001$ vs $p = 0.001$] and showing a significant interaction between both types of speech features; in exemption was N1 amplitude do not evidence any significant interaction between factor [N1: $p = 0.075$, $p = 0.038$; P3: $p = 0.042$, $p = 0.003$]. We found that the MMN response showing significant difference on amplitude and latency in response to /ba-da/ stimulus compared to the /ba-pa/ stimulus [$p = 0.036$ and $p = 0.004$]. Similarly, no interactions reached statistical significance between both sets of speech stimulus.

# CHAPTER 5: DISCUSSION

## 5.1 Main findings

The auditory evoked responses were successfully recorded from both study groups. Independent t-test showed there was no significant difference in age between the control group (NH) and the sensorineural hearing loss (SNHL) patient ($p$ = 0.181, df = 22). In this study, only Cz electrode was selected for further analysis as it has the most significant effects towards cortical auditory evoked potential (CAEP) waveforms in response to speech stimuli besides showing the highest signal to noise ratio compared to other electrode sites (Duncan et al., 2009; Korczak & Stapells, 2010; Schröder et al., 2014; Steinhauer, 2014; Wunderlich & Cone-Wesson, 2001). We discovered that the central electrode (Cz) is providing clearer and more stable CAEP waveforms compared to the fronto-electrode (Fz) on both speech stimuli circumvent both experimental groups. As per the result obtained, the presentation of MMN response was maximal in the central electrode (Cz) compared to fronto-central electrode (Fz). This finding is in agreement with the previously reported studies (Duncan et al., 2009; Steinhauer, 2014).

The primary goal of the present study aimed to determine the implication of various speech phonological features towards amplitudes and latencies of late CAEPs components between healthy group and individuals suffering from SNHL on Malaysian Malay native speaker population. In general, the finding showed that the CAEP components were clearly elicited in response to both stimulus contrast. Correlation coefficient test showed high resemblance ($r^2$ = 0.825) between the present study and the previous similar studies done using English CV by native English speakers and the standard typical CAEPs responses (Näätänen, 1992; Rotteveel, 1990; Wunderlich & Cone-Wesson, 2001). Table 5.1 showed the percentage of detectability for the CAEPs waveforms across volunteers. P3 was the most detectable CAEPs components which appeared in 100 percent on both standard and deviant responses, collapsed across stimulus, within both study groups followed by N2, N1, P2 and finally P1 component which is having the least score of percentage (Korczak & Stapells, 2010).

Table 5.1: Percentage of detectability between both speech stimuli on CAEP components

| **Type of stimulus presentation** | **Percentage of detectability (%)** | | | | |
|---|---|---|---|---|---|
| *Control Participants* | *P1* | *N1* | *P2* | *N2* | *P3* |
| /ba-da/ stimulus | 75.0 | 87.5 | 78.3 | 100.0 | 100.0 |
| /ba-pa/ stimulus | 78.3 | 85.0 | 80.3 | 100.0 | 100.0 |
| *SNHL participants* | *P1* | *N1* | *P2* | *N2* | *P3* |
| /ba-da/ stimulus | 70.5 | 81.3 | 72.0 | 90.0 | 100.0 |
| /ba-pa/ stimulus | 75.5 | 76.3 | 73.5 | 95.0 | 100.0 |

## 5.2 Features of speech articulation effects on both P1 and P2 amplitudes and latencies responses

From the study, the most notable finding was the percentage of appearance for P1 component in response to the voicing contrast stimulus which was higher compared to place of articulation stimulus response [78.3% vs 75.0%]. Resemblance evidence was also found in SNHL group [75.5% vs 70.5%]. It is showed that the appearance of auditory P2 is greater in voicing contrast instead of place of articulation stimulus and it is applicable for both experimental groups [80.3% vs 78.3% and 73.5% vs 72%]. Obviously, P1 and P2 components both elicited higher mean amplitude in response to voicing contrast compared to the place of articulation stimulus. The result of P1 component reported here fostering similarity with the previous finding when the average amplitude elicited from the SNHL patient is higher than the control group regardless to both stimuli (Schröder et al., 2014). The previous study emphasized the difficulty to assess accurately the P1 component due to the interaction with C1 waves from a visual event-related potential (VERP) component which creates a major overlapping mechanism with the P1

CAEP component (Luck, 2005). Another noteworthy finding when the deviant stimulus of auditory P2 experienced some amplitude increment compared to standard type across both stimuli. This finding compliance with the earlier study when the researchers outlined the enhancement of the P2 component when targeting infrequent stimulation (Davies et al., 2010; Luck, 2005; Steinhauer, 2014).

## 5.3 Features of speech articulation effects on both N1 and N2 amplitudes and latencies responses

CAEP N1 component showed a higher percentage of appearance in placing contrast stimulus. Different condition displayed in N2 component when control groups elicited 100% existence across both speech stimuli while the hearing-impaired group showing some discrepancy in the percentage of detectability. We outlined that N1 component which originally arising from superior temporal gyrus region provided crucial aspects in performing spectral and temporal acoustic discrimination tasks during spatial attentional process between various speech features when its showing significant main effects on most of the ANOVAs testing (Luck, 2005; Näätänen & Picton, 1987). We reported that the average mean amplitude of the auditory N1 and N2 were attenuated in SNHL patients compared to normal subjects; suggesting the encoding deficits in auditory processing information of hearing impaired population. Our finding correlate with the previous study when low-level of N1 auditory response in misophonia patients were identified in comparison with the healthy controls subjects (Schröder et al., 2014). Same result was also demonstrated by aphasia group in response to speech syllables and tones (Becker & Reinvang, 2013). These similarities suggested that the centre auditory process of sensorineural patient might interfere with some speech perception disorder. Specifically, the deprivation situation was more prominent in the auditory N1 response towards the place of articulation feature compared to voice/voiceless stimulus. In contrast, there were no clear justification involving the resemblance finding between N1 and N2 components, however may indeed reflect the reliance of cortical auditory response towards spectral cues of speech signal (Bien et al., 2016; Carpenter & Shahin, 2013; Scharinger, Monahan, & Idsardi, 2016).

## 5.4 Implication of speech stimulus on mismatch negativity (MMN) response and P3 component

Theoretically, the auditory MMN response was revealed when a constant train of identical stimuli with 'new' afferent infrequent mismatching stimuli was presented to an individual auditory system. This response process automatically when perceiving incoming stimuli to a sensory memory trace of preceding stimuli which are not only sensitive to task-relevant condition, but also when the subjects merely ignore the stimulus stream for different task as advocated in the present study (Jacobsen et al., 2003; Luck, 2005; Näätänen, 1995; Steinhauer, 2014; Ylinen et al., 2006). Recent evidence illustrated the significant effects of complexity stimulus and frequency towards elements of CAEPs on passive listening conditions, thus convinced the existence of tonotopicity perspective on the auditory cortex (Wunderlich & Cone-Wesson, 2001). Previous researchers concluded that the human auditory system elicited greater brain response towards speech CV stimuli compared to tonal stimuli as reflected in higher MMN and P3a amplitude values (Jaramillo et al., 2001; Tavabi et al., 2009). Former studies also proposed that the enlargement of MMN amplitudes in native speakers with two non-native speaker groups indicates the activation of native-language phonetic prototypes (Picton et al., 1995; Ylinen et al., 2006). As per objective, the current study only included the native Malaysian Malay ethnic groups where Malay CV speech tokens were presented.

In the current research, we proposed that the MMN response were elicited in contrast to Malay CV stimuli due to the present of language memory traces and this finding support the previous decisions when MMN response was shown in speech stimuli and were enhance when the individuals having automated access to the native-language phonetic prototypes (Becker & Reinvang, 2007; Näätänen, 1995). Both normal and SNHL subjects exhibited parallel neurons activation when producing higher negativity response in voicing contrast stimulus. Our finding stated that the MMN response elicited by the SNHL patients was smaller (almost half of the activation) and recorded at longer latencies on both CVs speech stimuli in comparison with control. In other words, the difference in MMN auditory response of hearing impaired patients was found to reflect not only the detection of speech phonologic features, but also revealed the anomalies in physiological measure of automatic discriminant ability involving central processing in audition (Näätänen, 1995; Näätänen & Escera, 2000). Moreover, our finding also proposed the higher neuron activation and delayed latency response towards voicing contrast stimulus that happened to both groups. Fostering interest to extend the idea done by Pettigrew et.al when they investigate the impact of MMN component towards four distinct English CV stimulus (/de:/, /ge:/, /deI/ “day”, and /geI/ “gay”) on 12 native English speakers. They concluded larger MMN response  obtained at an earlier latency to the real word deviants among non-word standards with the same initial consonant (i.e., ‘’de’’ in the word ‘’day’’, ‘’ge’’ in the word ‘’gay’’) when compared with the responses to non-word deviants among word standards (‘’day’’ for ‘’de’’, ‘’gay’’ for ‘’ge’’)(Pettigrew et al., 2004).

The emergence of CAEP P3 component increases dramatically when having 100% appearance for all averages. The introduction of deviant stimuli resulting tremendous increment compared to other components; emphasizing the P3 component as the most influential element in understanding CAEPs waveforms in response to various speech phonologic features as it reflects an involuntary switching of passive listening to the odd or deviant stimulus (Reis & Iório, 2007). It is clearly recorded that the amplitudes and latencies of auditory P3 were affected by speech articulation features when SNHL participants exhibit dominant activation voltages and prolonged latencies in response to voice/voiceless distinction stimulus in contrast with healthy volunteers.

In this study, the congruence of majority of the result demonstrated larger CAEP amplitudes and longer latencies for response to the voicing contrast compared to the place of articulation across both participants' groups. A plausible explanation contributes to this pattern of responses may be related to the spectrum energy correlates within these sets of stimuli. Agung et al. (2006) expressed the domination of low-level spectral energy in speech sound which produced higher N1 and P2 amplitudes with longer latencies experienced on P1, N1 and P2 components in comparison with the speech sound having higher frequency spectral energy. One possible explanation coincides with the spectral difference occurred on the frequency fractionation between formant 1 [F1] and formant 2 [F2] frequencies of voicing contrast having approximately 700-1100 Hz which is wider compared to the place of articulation contrast which having 500-750 Hz formant separation as shown in Figure 1 (Korczak & Stapells, 2010; Ting et al., 2011; Wunderlich & Cone-Wesson, 2001). This condition likely increases difficulty to the brain speech discrimination on voicing contrast recognition in comparison with the two consonant contrasts, thus lead to wider activation of cortical neurons resulting higher voltage and delayed latency recorded during phonemes discriminant task. Recently, scientist provided evidence using functional magnetic resonance imaging (FMRI) and magnetoencephalography (MEG) techniques proving that the deeper part of the brain responds better towards high-frequency stimulation compared to superficial region of the human cortex which responds better to low frequency information which indirectly support the present finding on greater response amplitude (Tavabi et al., 2009; Yetkin, Roland, Christensen, & Purdy, 2004). Earlier studies also reported the higher amplitude response on speech stimulus due to the broad frequency spectrum in comparison with the tonal stimuli (Wunderlich, Cone-Wesson, & Shepherd, 2006).

Another possible explanation contributed to this finding was due to the increment in onset voicing duration of the Malay CV /ba-pa/ stimulus in comparison to placing contrast stimulus. As can be seen from Figure 5.1 which illustrated the spectrogram analysis associates with the three syllables stimuli presented in the current study, the voice onset time (VOT) duration differs between the three syllables. Namely, CV syllables /ba/ and /da/ stimuli have the same configuration of the vocal tract but differ in their VOT, as the release sound for /b/ takes a shorter time than for /d/. During the stimulus presentation involving CV transition, there were no great changes occurred in terms of VOT for /ba-da/ stimulus as both exert the same voicing pattern with negative VOT.

Conversely, during the CV transition in /ba-pa/ stimulus, there was a great alteration in voicing onset duration when the /pa/ syllable having positive VOT (longer), in which voicing for the vowel happens after the plosive burst. These temporal cues property act as a major identification of voiced and voiceless phoneme. The rapidly changes of formant transition during CV passage support the finding on higher amplitudes and prolongation timing responses of CAEPs components happened in voicing contrast stimulus, thus underlying brain discrimination process to be a difficult task to operate. Several trends have been to explore the interaction of human perceptual process with changes of VOT on various speech cues and how does these temporal cues able to diminish human auditory mechanism on individuals suffering from hearing loss (Bruhn; Specht, Baumgartner, Stadler, Hugdahl, & Pollmann, 2014; Veuillet, Magnan, Ecalle, Thai-Van, & Collet, 2007; Wunderlich et al., 2006).

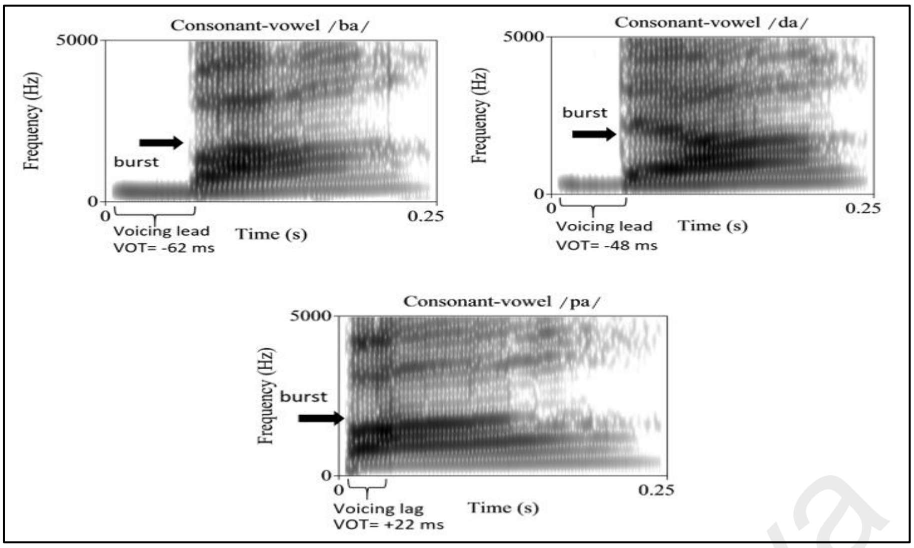


Figure 5.1: Comparison of sound spectrogram for the three used CV syllables /ba/, /da/, /pa/ in this study.

Last studied outlining the delayed neuronal synchronous response of the older adult population associated with disruption on the speech discrimination when dealing with time varying speech cues along /ba/ and /pa/ CVs token stimulus (Tremblay et al., 2002; Tremblay, Piskosz, et al., 2003). They outlined the larger amplitudes were experienced by older population and delayed response to stimuli with longer VOT duration. We conjecture that the sensorineural deficiency highly impacted on the ability of human auditory memory to conserve speech intelligibility between airflow blockage or constriction across location and the stimulus spectral voice-onset time duration compared to phonation in consonant sound property, thus contribute to the main hindrance in slowing down the capabilities of CAEP components in performing the discrimination task.

# CHAPTER 6: CONCLUSION AND FUTURE DIRECTIONS

In our study, done on local ethnic Malay population, the significance of cortical auditory evoked potential in discriminating speech acoustical complexity between various speech phonological properties involving people suffered from sensorineural hearing loss compared to normal individuals have been proved. The findings of this study exposed several key essences:

1. The mean CAEP amplitudes and latencies for most of the CAEP components were considerably larger and delayed in response to voicing contrast compared to placing contrast. This condition was more prominent in SNHL patients compared to that of the normal subjects. This result is likely due to the larger frequency spectral and longer time varying that present between these speech contrasts. Generally, effects changes of CAEPs response strength and response timing were clearly elicited within features of speech articulation. In addition, the results imply that the brain may have an easier task in discriminating placing contrast cues compared to voicing contrast. These CAEPs responses highlighted on how the speech signals were processed and variation responses happened between normal and nerve related hearing loss conditions.
2. MMN was clearly elicited in both study groups which support the evidence that the MMN is a tool in performing behavioral change detection as well as in the attention-dependent physiological measures of human auditory pathway. In the current study, the activation of MMN among SNHL subjects was almost ½ smaller and at longer latencies compared to that of the normal group. This discrepancy indirectly engaged with the fact that the automatic preconscious detection of auditory stimulus among SNHL subjects was much difficult and complex compared to the control group.

3. Present study justified the absence of relationship between the CAEPs and MMN in both study groups.

Restated, the present finding would be of great help to develop a possible clinical application in the SNHL population to enhance our knowledge regarding brain capabilities in discriminating various speech phonemes even in unwilling to cooperate clinical society. Future studies should investigate if there are any differences in CAEPs components on various speech articulation between normal hearing and hearing-impaired population while both groups were presented in passive and active listening condition. More extensive study is needed with bigger data population to verify the application of this brain mechanism towards society. Beneficial aspects of this extension will clarify how the discriminant task was performed in different attention variation through human auditory process in predicting both conditions; active and passive speech perception abilities between both groups. We believed that this feasibility study will be helpful for the design and development/manufacturing of future hearing assistive devices to those people suffering from SNHL, and finally towards the possible clinical application to the field of aural rehabilitation.

# REFERENCES

Aaltonen, O., Hellström, Å., Peltola, M. S., Savela, J., Tamminen, H., & Lehtola, H. (2008). Brain responses reveal hardwired detection of native-language rule violations. *Neuroscience letters, 444*(1), 56-59.

Abbs, J. H., & Sussman, H. M. (1971). Neurophysiological feature detectors and speech perception: A discussion of theoretical implications. *Journal of Speech, Language, and Hearing Research, 14*(1), 23-36.

Agung, K., Purdy, S. C., McMahon, C. M., & Newall, P. (2006). The use of cortical auditory evoked potentials to evaluate neural encoding of speech sounds in adults. *Journal of the American academy of audiology, 17*(8), 559-572.

Akeroyd, M. A. (2008). Are individual differences in speech reception related to individual differences in cognitive ability? A survey of twenty experimental studies with normal and hearing-impaired adults. *International journal of audiology, 47*(sup2), S53-S71.

Anderson, S., & Kraus, N. (2011). *Neural Encoding of Speech and Music: Implications for Hearing Speech in Noise.* Paper presented at the Seminars in hearing.

Anderson, S., Parbery-Clark, A., White-Schwoch, T., Drehobl, S., & Kraus, N. (2013). Effects of hearing loss on the subcortical representation of speech cues. *The Journal of the Acoustical Society of America, 133*(5), 3030-3038.

Annett, M. (1975). Hand preference and the laterality of cerebral speech. *Cortex, 11*(4), 305-328.

Arsenault, J. S., & Buchsbaum, B. R. (2015). Distributed Neural Representations of Phonological Features during Speech Perception. *The Journal of Neuroscience, 35*(2), 634-642.

Association, A. S.-L.-H. (2005). Guidelines for manual pure-tone threshold audiometry.

Başar, E., Başar-Eroğlu, C., Karakaş, S., & Schürmann, M. (1999). Are cognitive processes manifested in event-related gamma, alpha, theta and delta oscillations in the EEG? *Neuroscience letters, 259*(3), 165-168.

Başar, E., Gönder, A., & Ungan, P. (1976). Important relation between EEG and brain evoked potentials. *Biological Cybernetics, 25*(1), 41-48.

Basar, E., Rosen, B., Basar-Eroglu, C., & Greitschus, F. (1987). The associations between 40 Hz-EEG and the middle latency response of the auditory evoked potential. *International Journal of Neuroscience, 33*(1-2), 103-117.

Becker, F., & Reinvang, I. (2007). Mismatch negativity elicited by tones and speech sounds: Changed topographical distribution in aphasia. *Brain and language, 100*(1), 69-78.

Becker, F., & Reinvang, I. (2013). Identification of target tones and speech sounds studied with event-related potentials: Language-related changes in aphasia. *Aphasiology, 27*(1), 20-40. doi:10.1080/02687038.2012.676163

Bidelman, G. M. (2015). Towards an optimal paradigm for simultaneously recording cortical and brainstem auditory evoked potentials. *Journal of neuroscience methods*.

Bien, H., Hanulikova, A., Weber, A., & Zwitserlood, P. (2016). A neurophysiological investigation of non-native phoneme perception by Dutch and German listeners. *Frontiers in psychology, 7*, 56.

Billings, C. J., Tremblay, K. L., Souza, P. E., & Binns, M. A. (2007). Effects of hearing aid amplification and stimulus intensity on cortical auditory evoked potentials. *Audiology and Neurotology, 12*(4), 234-246.

Blanco-Velasco, M., Weng, B., & Barner, K. E. (2008). ECG signal denoising and baseline wander correction based on the empirical mode decomposition. *Computers in biology and medicine, 38*(1), 1-13.

Bley-Vroman, R. (1989). What is the logical problem of foreign language learning. *Linguistic perspectives on second language acquisition*, *4*, 1-68.

Boersma, P., & Weenink, D. (2015). Praat: Doing phonetics by computer (Version 5.2. 18)[Computer software].

Bonte, M., Hausfeld, L., Scharke, W., Valente, G., & Formisano, E. (2014). Task-dependent decoding of speaker and vowel identity from auditory cortical response patterns. *The Journal of Neuroscience, 34*(13), 4548-4557.

Boothroyd, A. (1993). Speech perception, sensorineural hearing loss, and hearing aids. *Acoustical factors affecting hearing aid performance, 2*, 277-279.

Boothroyd, A. (2007). Adult aural rehabilitation: What is it and does it work? *Trends in Amplification, 11*(2), 63-71.

Bruhn, D. W. Speaker Ethnicity as a Perceptual Shift Trigger.

Brussé, I., van den Berg, C., Duvekot, J., & Visser, G. (2015). O69. Visual evoked potential as neurophysiological evaluation of patients with severe PE and visual disturbances. *Pregnancy Hypertension: An International Journal of Women's Cardiovascular Health, 5*(3), 226-227.

Carballo-gonzalez, J. A., Valdes-sosa, P., & Valdes-sosa, M. (1989). Detection of Event Related Potentials. *International Journal of Neuroscience, 46*(3-4), 109-122. doi:10.3109/00207458908986247

Carpenter, A. L., & Shahin, A. J. (2013). Development of the N1–P2 auditory evoked response to amplitude rise time and rate of formant transition of speech sounds. *Neuroscience letters, 544*, 56-61.

Cheour, M., Alho, K., Čeponiené, R., Reinikainen, K., Sainio, K., Pohjavuori, M., . . . Näätänen, R. (1998). Maturation of mismatch negativity in infants. *International Journal of Psychophysiology, 29*(2), 217-226.

Chittka, L., & Brockmann, A. (2005). Perception space—the final frontier. *PLoS Biol, 3*(4), e137.

Clark, J. G. (1981). Uses and abuses of hearing loss classification. *Asha, 23*(7), 493-500.

Coburn, K. L., Arruda, J. E., Estes, K. M., & Amoss, R. T. (2014). Diagnostic utility of visual evoked potential changes in Alzheimer's disease. *The Journal of neuropsychiatry and clinical neurosciences*.

Collins, M. P., Liu, C.-F., Taylor, L., Souza, P. E., & Yueh, B. (2013). Hearing aid effectiveness after aural rehabilitation: Individual versus group trial results. *Journal of rehabilitation research and development, 50*(4), 585-598.

Cook, P. R., Music, C., & Sound, C. (1999). An Introduction to Psychoacoustics: MIT Press, Cambridge Massachusetts.

Csepe, V., & Molnar, M. (1997). Towards the possible clinical application of the mismatch negativity component of event-related potentials. *Audiology and Neurotology, 2*(5), 354-369.

Danermark, B., Manchaiah, V., Rönnberg, J., & Lunner, T. (2014). Importance of" Process valuation" in Audiological Rehabilitation: Examples from Studies on Hearing Impariment. *International Journal of Otolaryngology*.

Davies, P. L., Chang, W.-P., & Gavin, W. J. (2010). Middle and late latency ERP components discriminate between adults, typical children, and children with sensory processing disorders. *Frontiers in integrative neuroscience, 4*.

Dehaene-Lambertz, G., & Baillet, S. (1998). A phonological representation in the infant brain. *Neuroreport, 9*(8), 1885-1888.

Delattre, P., Liberman, A. M., Cooper, F. S., & Gerstman, L. J. (1952). An experimental study of the acoustic determinants of vowel color; observations on one-and two-formant vowels synthesized from spectrographic patterns. *Word*.

Department of Occupational Safety and Health (DOSH) Ministry of Human Resources. (2015). Occupational Disease and Poisoning Investigation.

Duncan, C. C., Barry, R. J., Connolly, J. F., Fischer, C., Michie, P. T., Näätänen, R., . . . Van Petten, C. (2009). Event-related potentials in clinical research: guidelines for eliciting, recording, and quantifying mismatch negativity, P300, and N400. *Clinical Neurophysiology, 120*(11), 1883-1908.

Duncan, J., Rhoades, E. A., & Fitzpatrick, E. M. (2014). *Auditory (Re) Habilitation for Adolescents with Hearing Loss: Theory and Practice*: Oxford University Press.

Edmonds, B. A., James, R. E., Utev, A., Vestergaard, M. D., Patterson, R. D., & Krumbholz, K. (2010). Evidence for early specialized processing of speech formant information in anterior and posterior human auditory cortex. *European Journal of Neuroscience, 32*(4), 684-692.

Fifer, R. C. (1997). Hair Cells and Hearing Aids. *Ear and hearing, 18*(2), 167.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": a practical method for grading the cognitive state of patients for the clinician. *Journal of psychiatric research, 12*(3), 189-198.

Fu, Q.-J., Galvin, J., Wang, X., & Nogaki, G. (2005). Moderate auditory training can improve speech performance of adult cochlear implant patients. *Acoustics Research Letters Online*, *6*(3), 106-111.

Gerken, G. M., Hesse, P. S., & Wiorkowski, J. J. (2001). Auditory evoked responses in control subjects and in patients with problem-tinnitus. *Hearing research, 157*(1), 52-64.

Gloor, P. (1969). Hans Berger on Electroencephalography. *American Journal of EEG Technology*, *9*(1), 1-8.

Golder, F., Walsh, E., Buchanan, A., & Lind, C. (2012). Attendees' perceptions of, motivation for and outcomes, following an adult group aural rehabilitation program. *Australian and New Zealand Journal of Audiology, The, 32*(2), 73.

Gordon-Salant, S. (2005). Hearing loss and aging: new research findings and clinical implications. *Journal of rehabilitation research and development, 42*(4), 9.

Gordon-Salant, S. (2014). Aging, Hearing Loss, and Speech Recognition: Stop Shouting, I Can't Understand You *Perspectives on Auditory Research* (pp. 211-228): Springer.

Henoch, M. A. (1991). Speech perception, hearing aid technology, and aural rehabilitation: A future perspective. *Ear and hearing, 12*(6), 187S-191S.

Jacobsen, T. (2004). Mismatch negativity to frequency changes: no evidence from human event-related brain potentials for categorical speech processing of complex tones resembling vowel formant structure. *Neuroscience letters, 362*(3), 204-208.

Jacobsen, T., Schröger, E., Horenkamp, T., & Winkler, I. (2003). Mismatch negativity to pitch change: varied stimulus proportions in controlling effects of neural refractoriness on human auditory event-related brain potentials. *Neuroscience letters*, *344*(2), 79-82.

Jacobson, G. P., Calder, J. A., Newman, C. W., Peterson, E. L., Wharton, J. A., & Ahmad, B. (1996). Electrophysiological indices of selective auditory attention in subjects with and without tinnitus. *Hearing research*, *97*(1), 66-74.

Jacobson, G. P., Lombardi, D. M., Gibbens, N. D., Ahmad, B., & Newman, C. W. (1992). The effects of stimulus frequency and recording site on the amplitude and latency of multichannel cortical auditory evoked potential (CAEP) component N1. *Ear and hearing, 13*(5), 300-306.

Jaramillo, M., Ilvonen, T., Kujala, T., Alku, P., Tervaniemi, M., & Alho, K. (2001). Are different kinds of acoustic features processed differently for speech and non-speech sounds? *Cognitive brain research, 12*(3), 459-466.

Kavaklioglu, T., Guadalupe, T., Zwiers, M., Marquand, A. F., Onnink, M., Shumskaya, E., . . . Francks, C. (2017). Structural asymmetries of the human cerebellum in relation to cerebral cortical asymmetries and handedness. *Brain Structure and Function, 222*(4), 1611-1623.

Kemp, D. T. (1978). Stimulated acoustic emissions from within the human auditory system. *The Journal of the Acoustical Society of America, 64*(5), 1386-1391.

Kochkin, S. (2005a). The impact of untreated hearing loss on household income. *Better Hearing Institute*.

Kochkin, S. (2005b). MarkeTrak VII: Hearing loss population tops 31 million people. *Hearing review, 12*(7), 16-29.

König, O., Schaette, R., Kempter, R., & Gross, M. (2006). Course of hearing loss and occurrence of tinnitus. *Hearing research, 221*(1), 59-64.

Korczak, P. A., Kurtzberg, D., & Stapells, D. R. (2005a). Effects of sensorineural hearing loss and personal hearing AIDS on cortical event-related potential and behavioral measures of speech-sound processing. *Ear Hear, 26*(2), 165-185.

Korczak, P. A., Kurtzberg, D., & Stapells, D. R. (2005b). Effects of sensorineural hearing loss and personal hearing aids on cortical event-related potential and behavioral measures of speech-sound processing. *Ear and hearing, 26*(2), 165-185.

Korczak, P. A., & Stapells, D. R. (2010). Effects of various articulatory features of speech on cortical event-related potentials and behavioral measures of speech-sound processing. *Ear and hearing, 31*(4), 491-504.

Korpilahti, P., Krause, C. M., Holopainen, I., & Lang, A. H. (2001). Early and late mismatch negativity elicited by words and speech-like stimuli in children. *Brain and language, 76*(3), 332-339.

Ladefoged, P., & Maddieson, I. (1998). The sounds of the world's languages. *Language, 74*(2), 374-376.

Lee, C.-Y., Jaw, F.-S., Pan, S.-L., Lin, M.-Y., & Young, Y.-H. (2007). Auditory cortical evoked potentials in tinnitus patients with normal audiological presentation. *Journal of the Formosan Medical Association, 106*(12), 979-985.

Liu, X., & Yan, D. (2007). Ageing and hearing loss. *The Journal of pathology, 211*(2), 188-197.

Luck, S. (2005). An Introduction to Event-Related Potentials and their Neural Origins (Chapter 1): Cambridge: MIT Press.

Lutman, M. E., Gatehouse, S., & Worthington, A. G. (1991). Frequency resolution as a function of hearing threshold level and age. *The Journal of the Acoustical Society of America, 89*(1), 320-328.

Maiste, A. C., Wiens, A. S., Hunt, M. J., Scherg, M., & Picton, T. W. (1995). Event-related potentials and the categorical perception of speech sounds. *Ear and hearing, 16*(1), 68-89.

Manchaiah, V., Baguley, D. M., Pyykkö, I., Kentala, E., & Levo, H. (2015). Positive experiences associated with acquired hearing loss, Ménière's disease, and tinnitus: A review. *International journal of audiology*(0), 1-10.

Martin, B. A., & Boothroyd, A. (2000). Cortical, auditory, evoked potentials in response to changes of spectrum and amplitude. *The Journal of the Acoustical Society of America, 107*(4), 2155-2161.

Martin, J. S., & Jerger, J. F. (2005). Some effects of aging on central auditory processing. *Journal of rehabilitation research and development, 42*(4), 25.

Martin, L., Barajas, J. J., Fernandez, R., & Torres, E. (1988). Auditory event-related potentials in well-characterized groups of children. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 71*(5), 375-381.

McCarthy, G., & Wood, C. C. (1985). Scalp distributions of event-related potentials: an ambiguity associated with analysis of variance models. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 62*(3), 203-208.

Medland, S. E., Duffy, D. L., Wright, M. J., Geffen, G. M., Hay, D. A., Levy, F., . . . White, V. (2009). Genetic influences on handedness: data from 25,732 Australian and Dutch twin families. *Neuropsychologia, 47*(2), 330-337.

Mesgarani, N., Cheung, C., Johnson, K., & Chang, E. F. (2014). Phonetic feature encoding in human superior temporal gyrus. *Science, 343*(6174), 1006-1010.

Mji, G. (2001). International Classification of Functioning, Disability & Health.

Modugumudi, Y. R., Santhosh, J., & Anand, S. (2013). Efficacy of Collaborative Virtual Environment Intervention Programs in Emotion Expression of Children with Autism. *Journal of Medical Imaging and Health Informatics, 3*(2), 321-325.

Moore, B. C. (2010). The relationship between tinnitus pitch and the edge frequency of the audiogram in individuals with hearing impairment and tonal tinnitus. *Hearing research, 261*(1), 51-56.

Moore, D. (1993). Plasticity of binaural hearing and some possible mechanisms following late-onset deprivation. *Journal of the American academy of audiology, 4*(5), 277-283; discussion 283-274.

Näätänen, R. (1992). *Attention and brain function*: Psychology Press.

Näätänen, R. (1995). The mismatch negativity: a powerful tool for cognitive neuroscience. *Ear and hearing, 16*(1), 6-18.

Näätänen, R. (2001). The perception of speech sounds by the human brain as reflected by the mismatch negativity (MMN) and its magnetic equivalent (MMNm). *Psychophysiology, 38*(1), 1-21.

Näätänen, R. (2008). Mismatch negativity (MMN) as an index of central auditory system plasticity. *International journal of audiology, 47*(sup2), S16-S20.

Näätänen, R., & Escera, C. (2000). Mismatch negativity: clinical and other applications. *Audiology and Neurotology, 5*(3-4), 105-110.

Näätänen, R., Paavilainen, P., Titinen, H., Jiang, D., & Alho, K. (1993). Attention and mismatch negativity. *Psychophysiology, 30*(5), 436-450.

Näätänen, R., & Picton, T. (1987). The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component structure. *Psychophysiology, 24*(4), 375-425.

Nadol, J. B. (1993). Hearing Loss. *New England Journal of Medicine, 329*(15), 1092-1102. doi:doi:10.1056/NEJM199310073291507

Neuman, A. C. (2005). Central auditory system plasticity and aural rehabilitation of adults. *Journal of rehabilitation research and development, 42*(4), 169.

Oates, P. A., Kurtzberg, D., & Stapells, D. R. (2002a). Effects of sensorineural hearing loss on cortical event-related potential and behavioral measures of speech-sound processing. *Ear Hear, 23*(5), 399-415. doi:10.1097/01.aud.0000034777.12562.31

Oates, P. A., Kurtzberg, D., & Stapells, D. R. (2002b). Effects of sensorineural hearing loss on cortical event-related potential and behavioral measures of speech-sound processing. *Ear and hearing, 23*(5), 399-415.

Oberman, L. M., Hubbard, E. M., McCleery, J. P., Altschuler, E. L., Ramachandran, V. S., & Pineda, J. A. (2005). EEG evidence for mirror neuron dysfunction in autism spectrum disorders. *Cognitive brain research, 24*(2), 190-198.

Obleser, J., Eulitz, C., Lahiri, A., & Elbert, T. (2001). Gender differences in functional hemispheric asymmetry during processing of vowels as reflected by the human brain magnetic response. *Neuroscience letters, 314*(3), 131-134.

Obleser, J., Lahiri, A., & Eulitz, C. (2004). Magnetic brain response mirrors extraction of phonological features from spoken vowels. *Journal of Cognitive Neuroscience, 16*(1), 31-39.

Ostroff, J. M., Martin, B. A., & Boothroyd, A. (1998). Cortical evoked response to acoustic change within a syllable. *Ear and hearing, 19*(4), 290-297.

Peterson, G. E., & Barney, H. L. (1952). Control methods used in a study of the vowels. *The Journal of the Acoustical Society of America, 24*(2), 175-184.

Pettigrew, C. M., Murdoch, B. E., Ponton, C. W., Finnigan, S., Alku, P., Kei, J., . . . Chenery, H. J. (2004). Automatic auditory processing of English words as indexed by the mismatch negativity, using a multiple deviant paradigm. *Ear and hearing, 25*(3), 284-301.

Pfefferbaum, A., Ford, J. M., Roth, W. T., & Kopell, B. S. (1980). Age-related changes in auditory event-related potentials. *Electroencephalography and clinical neurophysiology, 49*(3), 266-276.

Picton, T., Bentin, S., Berg, P., Donchin, E., Hillyard, S., Johnson, R., . . . Rugg, M. (2000). Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. *Psychophysiology, 37*(02), 127-152.

Picton, T. W., Lins, O. G., & Scherg, M. (1995). The recording and analysis of event-related potentials. *Handbook of neuropsychology, 10*, 3-3.

Ponton, C. W., Vasama, J.-P., Tremblay, K., Khosla, D., Kwong, B., & Don, M. (2001). Plasticity in the adult human central auditory system: evidence from late-onset profound unilateral deafness. *Hearing research, 154*(1), 32-44.

Pratt, H., Starr, A., Michalewski, H. J., Dimitrijevic, A., Bleich, N., & Mittelman, N. (2009). Auditory-evoked potentials to frequency increase and decrease of high- and low-frequency tones. *Clinical Neurophysiology, 120*(2), 360-373.

Rapin, I., & Graziani, L. J. (1967a). Auditory-evoked responses in normal, brain-damaged, and deaf infants. *Neurology, 17*(9), 881-894.

Rapin, I., & Graziani, L. J. (1967b). Auditory‐evoked responses in normal, brain‐damaged, and deaf infants. *Neurology, 17*(9), 881-881.

Rauschecker, J. P. (1999). Auditory cortical plasticity: a comparison with other sensory systems. *Trends in neurosciences, 22*(2), 74-80.

Reis, A. C. M. B., & Iório, M. C. M. (2007). P300 in subjects with hearing loss. *Pró-Fono Revista de Atualização Científica, 19*(1), 113-122.

Roets-Merken, L. M., Draskovic, I., Zuidema, S. U., van Erp, W. S., Graff, M. J., Kempen, G. I., & Vernooij-Dassen, M. J. (2014). Effectiveness of rehabilitation interventions in improving emotional and functional status in hearing or visually impaired older adults: a systematic review with meta-analyses. *Clinical rehabilitation*, 0269215514542639.

Rosburg, T., Haueisen, J., & Sauer, H. (2002). Habituation of the auditory evoked field component N100m and its dependence on stimulus duration. *Clinical Neurophysiology, 113*(3), 421-428.

Rosdina, A., Leelavathi, M., Zaitun, A., Lee, V., Azimah, M., Majmin, S., & Mohd, K. (2010). Self reported hearing loss among elderly Malaysians. *Malaysian family physician: the official journal of the Academy of Family Physicians of Malaysia, 5*(2), 91.

Rosdina, A., Leelavathi, M., Zaitun, A., Lee, V., Azimah, M., Majmin, S., & Mohd, K. (2012). Self reported hearing loss among elderly Malaysians. *Malaysian Family Physician, 5*(2), 4.

Rotteveel, J. (1990). Middle and long latency auditory evoked potentials *Evoked Potential Manual* (pp. 79-114): Springer.

Ruffini, G., Dunne, S., Farrés, E., Cester, I., Watts, P. C., Ravi, S., . . . Marco-Pallares, J. (2007). *ENOBIO dry electrophysiology electrode; first human trial plus wireless electrode system.* Paper presented at the Engineering in Medicine and Biology Society, 2007. EMBS 2007. 29th Annual International Conference of the IEEE.

Ruffini, G., Dunne, S., Farrés, E., Marco-Pallarés, J., Ray, C., Mendoza, E., . . . Grau, C. (2006). A dry electrophysiology electrode using CNT arrays. *Sensors and Actuators A: Physical, 132*(1), 34-41.

Salisbury, D. F., Collins, K., & McCarley, R. W. (2009). Reductions in the N1 and P2 auditory event-related potentials in first-hospitalized and chronic schizophrenia. *Schizophrenia bulletin*, sbp003.

Sams, M., Paavilainen, P., Alho, K., & Näätänen, R. (1985). Auditory frequency discrimination and event-related potentials. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 62*(6), 437-448.

Scharinger, M., Monahan, P. J., & Idsardi, W. J. (2016). Linguistic category structure influences early auditory processing: Converging evidence from mismatch responses and cortical oscillations. *NeuroImage*.

Schnupp, J., Nelken, I., & King, A. (2011). *Auditory neuroscience: Making sense of sound*: MIT Press.

Schröder, A., van Diepen, R., Mazaheri, A., Petropoulos-Petalas, D., de Amesti, V. S., Vulink, N., & Denys, D. (2014). Diminished N1 auditory evoked potentials to oddball stimuli in misophonia patients. *Frontiers in behavioral neuroscience, 8*.

Sharma, A., Marsh, C. M., & Dorman, M. F. (2000). Relationship between N1 evoked potential morphology and the perception of voicing. *The Journal of the Acoustical Society of America, 108*(6), 3030-3035.

Shi, S.-J., & Lu, B.-L. (2009). *EEG signal classification during listening to native and foreign languages songs.* Paper presented at the Neural Engineering, 2009. NER'09. 4th International IEEE/EMBS Conference on.

Simpson, J. (1974). EVOKED POTENTIALS IN PSYCHOLOGY, SENSORY PHYSIOLOGY AND CLINICAL MEDICINE. *Journal of neurology, neurosurgery, and psychiatry, 37*(5), 615.

Skagerstrand, Å., Stenfelt, S., Arlinger, S., & Wikström, J. (2014). Sounds perceived as annoying by hearing-aid users in their daily soundscape. *International journal of audiology, 53*(4), 259-269.

Specht, K., Baumgartner, F., Stadler, J., Hugdahl, K., & Pollmann, S. (2014). Functional asymmetry and effective connectivity of the auditory system during speech perception is modulated by the place of articulation of the consonant–A 7T fMRI study.

Stapells, D. (2002). Cortical event-related potentials to auditory stimuli. *Handbook of clinical audiology, 5*, 378-406.

Steinhauer, K. (2014). Event-related potentials (ERPs) in second language research: a brief introduction to the technique, a selected review, and an invitation to reconsider critical periods in L2. *Applied Linguistics*, amu028.

Stevens, K. N., & Blumstein, S. E. (1978). Invariant cues for place of articulation in stop consonants. *The Journal of the Acoustical Society of America, 64*(5), 1358-1368.

Stewart, R., & Wingfield, A. (2009). Hearing loss and cognitive effort in older adults' report accuracy for verbal materials. *Journal of the American academy of audiology, 20*(2), 147.

Syka, J. (2002). Plastic changes in the central auditory system after hearing loss, restoration of function, and during learning. *Physiological Reviews, 82*(3), 601-636.

Tampas, J. W., Harkrider, A. W., & Hedrick, M. S. (2005). Neurophysiological indices of speech and nonspeech stimulus processing. *Journal of Speech, Language, and Hearing Research, 48*(5), 1147-1164.

Tavabi, K., Elling, L., Dobel, C., Pantev, C., & Zwitserlood, P. (2009). Effects of place of articulation changes on auditory neural activity: A magnetoencephalography study. *PloS one, 4*(2), e4452-e4452.

Taylor, M. J. (1988). Developmental changes in ERPs to visual language stimuli. *Biological Psychology, 26*(1), 321-338.

Ting, H. N., Chia, S. Y., Hamid, B. A., & Mukari, S. Z.-M. S. (2011). Acoustic characteristics of vowels by normal Malaysian Malay young adults. *Journal of Voice, 25*(6), e305-e309.

Tremblay, K., & Burkard, R. (2007). The aging auditory system: confounding effects of hearing loss on AEPs. *Auditory Evoked Potentials. Baltimore: Lippincot Williams & Wilkins*, 403-425.

Tremblay, K., Friesen, L., Martin, B., & Wright, R. (2003). Test-retest reliability of cortical evoked potentials using naturally produced speech sounds. *Ear and hearing, 24*(3), 225-232.

Tremblay, K. L., Piskosz, M., & Souza, P. (2002). Aging alters the neural representation of speech cues. *Neuroreport, 13*(15), 1865-1870.

Tremblay, K. L., Piskosz, M., & Souza, P. (2003). Effects of age and age-related hearing loss on the neural representation of speech cues. *Clinical Neurophysiology, 114*(7), 1332-1343.

Veuillet, E., Magnan, A., Ecalle, J., Thai-Van, H., & Collet, L. (2007). Auditory processing disorder in children with reading disabilities: effect of audiovisual training. *Brain, 130*(11), 2915-2928.

Walpurger, V., Hebing-Lennartz, G., Denecke, H., & Pietrowsky, R. (2003). Habituation deficit in auditory event-related potentials in tinnitus complainers. *Hearing research*, *181*(1), 57-64.

Wayner, D. S. (2005). Aural rehabilitation adds value, lifts satisfaction, cuts returns. *The Hearing Journal, 58*(12), 30-38.

Wolfe, L. (2011). Beyond hearing aid fitting: Patient-centered aural rehabilitation in adults with acquired sensorineural hearing impairment.

Wunderlich, J. L., & Cone-Wesson, B. K. (2001). Effects of stimulus frequency and complexity on the mismatch negativity and other components of the cortical auditory-evoked potential. *The Journal of the Acoustical Society of America, 109*(4), 1526-1537.

Wunderlich, J. L., Cone-Wesson, B. K., & Shepherd, R. (2006). Maturation of the cortical auditory evoked potential in infants and young children. *Hearing research, 212*(1), 185-202.

Yetkin, F. Z., Roland, P. S., Christensen, W. F., & Purdy, P. D. (2004). Silent functional magnetic resonance imaging (FMRI) of tonotopicity and stimulus intensity coding in human primary auditory cortex. *The Laryngoscope, 114*(3), 512-518.

Ylinen, S., Shestakova, A., Huotilainen, M., Alku, P., & Näätänen, R. (2006). Mismatch negativity (MMN) elicited by changes in phoneme length: a cross-linguistic study. *Brain research, 1072*(1), 175-185.

Zheng, H.-Y., Minett, J. W., Peng, G., & Wang, W. S. Y. (2012). The impact of tone systems on the categorical perception of lexical tones: An event-related potentials study. *Language and Cognitive Processes, 27*(2), 184-209. doi:10.1080/01690965.2010.520493

# LIST OF PUBLICATIONS AND PAPERS PRESENTED

**Journal Publications:**

1. **Abdul Rauf Abu Bakar,** Jayasree Santhosh, Mohamad Gamal Al-Zidi, Ibrahim Amer Ibrahim, Hua Nong Ting, Siew Cheok Ng, Effects of speech phonological features during passive perception on cortical auditory evoked potential in sensorineural hearing loss; **Sains Malaysiana** (ISI-Cited Publication), **(accepted)**
2. Muhamad Gamal Al-Zidi, Jayasree Santhosh, Siew Cheok Ng, **Abdul Rauf Abu Bakar,** Ibrahim Amer Ibrahim, Cortical auditory evoked potentials as indicators of hearing aids performance in speech perception; **Journal of Engineering Research** (ISI-Cited Publication), **(Published online)**
3. Ibrahim Amer Ibrahim, Jayasree Santhosh, Mohamad Gamal Al-Zidi, **Abdul Rauf Abu Bakar**, The significant effect of pure tone and consonant-vowel stimuli on auditory evoked potential in normal hearing Malay adults, **Hindawi** (ISI-Cited Publication), **(under review)**

**Conference:**

1. **Abdul Rauf Abu Bakar,** Jayasree Santhosh, Analysis on encoding mechanism in brain for amputee rehabilitation: A pilot study using 'Mirror Neuron Systems', 2015 **IEEE International Conference on Control System, Computing and Engineering (ICCSCE),** DOI: 10.1109/ICCSCE.2015.7482166 **(proceeding)**