FUNCTIONAL EFFECTS OF CORTICAL AUDITORY EVOKED POTENTIALS AND HEARING AIDS ON SPEECH PERCEPTION IN SENSORINEURAL HEARING LOSS INDIVIDUALS

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DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2018

UNIVERSITY OF MALAYA

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ABSTRACT

Cortical Auditory Evoked Potentials (CAEPs) represent summation of neural activity in the auditory pathways in reaction to sounds. They provide an objective measure of the brain's response to sound. For this reason, CAEPs are an ideal tool for scientists and audiologists for investigating auditory function in people both, normal and with hearing loss. The main objective of this study is to determine which CAEP components among the P1, N1, P2, N2, or P3 are most beneficial in assessing the speech detection and discrimination abilities of adults Sensorineural Hearing Loss (SNHL) population. This study also intends to investigate whether changes in the amplitudes and latencies of these CAEP components occurring with SNHL and hearing aids reflect various stages of auditory processing. CAEPs were recorded from two groups of participants. A control group that comprising of 12 right-handed Malay adults having normal hearing and a second group that consists of 10 right-handed Malay adults with sensorineural hearing loss who were recruited from the local community in the department of Otorhinolaryngology (ENT), UMMC hospital, Kuala Lumpur. The results showed that P2 and P3 components had the most benefits from the use of hearing aids in the SNHL subjects and could be used in both clinical and research applications as a predictor and objective indicator of hearing aids performance in speech perception. The study also showed that the brain processes both stimuli in a different pattern for both normal and aided SNHL subjects. These findings suggest that the aided SNHL subject, despite the benefits they get from the hearing aids, find it difficult to detect and discriminate the acoustic differences between the two speech stimuli. The present study could provide more diagnostic information for clinicians and could also offer better speech perception benefits for hearing-impaired individuals from their personal hearing aids.

ABSTRAK

Kortikal Auditory menimbulkan potensi (CAEPs) mewakili penjumlahan aktiviti neural dalam laluan auditori sebagai tindak balas kepada bunyi. Mereka menyediakan ukuran yang objektif tindak balas otak untuk bunyi. Atas sebab ini, CAEPs adalah alat yang ideal untuk ahli-ahli sains dan audiologis untuk menyiasat fungsi pendengaran pada orang kedua, normal dan dengan kehilangan pendengaran. Objektif utama kajian ini adalah untuk menentukan CAEP komponen antara P1, N1, P2, N2, atau P3 adalah yang paling bermanfaat dalam menilai pengesanan ucapan dan diskriminasi kebolehan penduduk pendengaran orang dewasa. Kajian ini juga bercadang untuk menyiasat sama ada perubahan dalam amplitud dan latencies daripada komponen CAEP berlaku dengan sensorineural Kehilangan Pendengaran (SNHL) dan alat pendengaran berbeza dalam jawapan mencerminkan peringkat pemprosesan auditori. CAEPs direkodkan daripada kedua-dua kumpulan peserta. Kumpulan kawalan dewasa yang terdiri daripada 12 orang dewasa Melayu tangan kanan yang mempunyai pendengaran normal dan kumpulan kedua terdiri daripada 10 orang dewasa Melayu tangan kanan dengan kehilangan pendengaran sensorineural yang telah diambil daripada masyarakat setempat di jabatan Otorinolaringologi (ENT), hospital PPUM, Kuala Lumpur. Hasil kajian menunjukkan bahawa P2 dan P3 komponen mempunyai manfaat yang paling dari penggunaan alat bantuan pendengaran dalam mata pelajaran SNHL dan boleh digunakan dalam kedua-dua aplikasi klinikal dan penyelidikan sebagai peramal dan penunjuk objektif pendengaran prestasi membantu dalam persepsi pertuturan. Kajian ini juga menunjukkan bahawa otak memproses kedua-dua rangsangan dalam corak yang berbeza untuk kedua-dua subjek SNHL normal dan dibantu. Penemuan ini menunjukkan bahawa SNHL subjek yang dibantu itu, walaupun manfaat yang mereka dapat dari alat bantuan pendengaran, mendapati sukar untuk mengesan dan membezakan perbezaan akustik antara kedua-dua rangsangan bersuara. Kajian ini boleh

memberikan maklumat yang lebih diagnostik untuk perubatan dan juga boleh menawarkan lebih baik manfaat persepsi ucapan untuk individu cacat pendengaran dari alat bantuan pendengaran peribadi mereka.

ACKNOWLEDGEMENTS

First of all, I would like to express my gratitude to Allah S.W.T. for His blessings and for giving me the strength along the challenging journey of completing this project.

I would also like to take this opportunity to extend my kind appreciation to my supervisors, Dr. Jayasree Santhosh and Dr. Ng Siew Cheok, who encouraged me throughout this journey. Their invaluable comments and feedback helped me in structuring my research work through the submission of this dissertation.

I would also like to convey my sincere gratitude to University of Malaya for its financial support under the University of Malaya Research Grant (UMRG), grant No: RP016D-13AET. Thank you.

Finally, I am constantly indebted to my parents and my siblings for their love, understanding and encouragement throughout my life. I would not be able to succeed in my thesis without their continuing patience and encouragement. I am also thankful to my friends who gave me the possibility to complete this dissertation.

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LIST OF SYMBOLS AND ABBREVIATIONS

For example:

SNHL	:	Sensorineural hearing loss
EEG	:	Electroencephalogram
CAEP	:	Cortical Auditory Evoked Potentials
ABR	:	Auditory Brainstem Response
MMSE	:	Mini Mental State Examination
CV	:	Consonant Vowel
EMD	:	Empirical Mode Decomposition
UMMC	:	University of Malaya Medical Centre
P1	:	Positive Deflection at 100 ms
P2	:	Positive Deflection at 200 ms
P3	:	Positive Deflection at 300 ms
N1	:	Negative Deflection at 100 ms
N2	:	Negative Deflection at 200 ms
DC	:	Direct Current
DRL	:	Driven Right Leg
ANOVA	:	Analysis of Variance
SD	:	Standard Deviation
MLAEP	:	Medal Latency Auditory Evoked Potentials
LLAEP	:	Late Latency Auditory Evoked Potentials
MLRs	:	Middle-Latency Responses
LAEPs	:	Long-Latency Auditory Evoked Potentials
LLAEP	:	Late Latency Auditory Evoked Potentials
ms	:	Millisecond

V	:	Volt
uV	:	Microvolt
Hz	:	Hertz
dB	:	Decibels
%	:	Percentage

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CHAPTER 1: INTRODUCTION

1.1 Background Study

Hearing loss is a common problem that could develop with age, caused by accident or by repeated exposure to loud noises. Sensorineural Hearing Loss (SNHL) is a second kind of hearing loss which occurs due to deficits in nerve pathways in either the inner ear, or central processing units of the brain. SNHL has different degrees including mild, moderate, severe, or profound, including total deafness. People with SNHL require hearing aids to improve their hearing and listening abilities. However, hearing aids do not usually restore hearing to normal and there are still difficulties to optimal speech perception. Hearing aids' fitting and evaluation have long proved difficult for audiologist. It is even more difficult when dealing with difficult-to-test patients. It requires thorough hearing tests to measure the softest sound one can hear at different levels of frequencies. These tests are normally conducted using Auditory Brainstem Response (ABR), Pure Tone Audiometry (PTA) and behavioral observation audiometry which require responses from candidates. However, with some patients (e.g., infants, children, and difficult-to-test indiviuals) Cortical Auditory Evoked Potential (CAEP) recording proved to be better applicable to hearing aid evaluation and has several advantages over ABR recording. Difficult-to-test hearing aids candidates are those whom it is troublesome (or sometimes impossible) to correctly carry out usual audiological assessments (e.g., ABR or PTA) (Ray, 2002). The "difficult to test" patients are those people who are in several or different ways referred to as intellectually disabled or intellectually impaired (Lennox, Beange, & Edwards, 2000), or as "developmentally disabled". Those patients also include people who are intentionally non-cooperative too.

CAEPs represent the summation of the activities of neurons in the auditory pathways in response to sounds. Due to the fact that CAEPs could tell us how the brain responses to sound, they are an ideal tool for examining brain's auditory function in people. CAEP has been recently used to evaluate the brain's cognitive processes that are required in the discrimination and detection of complex speech sounds in people with normal-hearing. Due to the fact that SNHL changes the timing, location and strength, of the cognitive brain processes related to the auditory perception, CAEPs could be used to assess how well or effectively the brain perceives the speech in persons having sensorineural hearing loss. Among the electrophysiological methods available, CAEP technique has been considered as the most suited technique for evaluating the capability of people to hear amplified speech using hearing aids (Souza & Tremblay, 2006).

CAEPs have several applications (Hyde, 1997). This was successfully used for the estimation of hearing threshold, as with the most recent studies. Estimation of cortical auditory responses has been clinically effective for hearing aid's evaluation (Carter, Dillon, Seymour, Seeto, & Van Dun, 2013) and cochlear implant fittings. CAEPs are sometimes used to track the maturation of the human auditory system and the impact of plasticity (Ponton, Eggermont, Kwong, & Don, 2000). Furthermore, CAEPs are useful in the examination of the brain's ability for auditory processing, auditory training, the effect of aging, loudness growth and comfortable levels (Burkard, Eggermont, & Don, 2007).

CAEP recording has several advantages compared to ABR and PTA recording. First, acoustic features—that are suitable for the identification and perception of speech presented as stimuli—can be handled with hearing aids reasonably well, as compared to ABR which uses clicks (Kurtzberg, Stapells, & Wallace, 1988). Second, CAEPs can assess the wholeness of the pathway of the response to the cortex whereas ABR only assesses the outer ear (N. Kraus, McGee, & Koch, 1998). Thus, CAEP's absence or presence in the brain correlates better with speech perception. Third, it is shown that in some conditions of auditory neuropathy spectrum disorder, CAEPs may be observed even when an ABR is absent (Pearce, Golding, & Dillon, 2007; Rance, Cone-Wesson, Wunderlich, & Dowell, 2002).

1.2 Problem Statement

Traditionally, hearing aid fitting and evaluation for SNHL candidates have relied heavily on PTA, ABR and BOA, which require responses from candidates and are limited in their effectiveness due to the fact that responses are not likely to happen consistently near the hearing threshold "true" (Thompson & Weber, 1974). In infant and difficult-to-test candidates, it is sometimes impossible to get any cooperation from candidates. In this case, CAEP assessment is used, in which, it does not rely on any cooperation from the subject. Therefore, knowing which component among P1, N1, P2, N2, or P3 of CAEP has most benefits in assessing the abilities of speech detection and discrimination of SNHL population could provide diagnostic information for clinicians and could also provide clinicians and audiologists with the perception benefits of speech that hearing-loss people get from using hearing aids. This information would also provide evidences that the speech sounds or signals have reached to the auditory cortex in a faster and more effective way and is therefore audible to the person wearing the hearing. Therefore, audiologist would be able to tell whether the patients could hear the sound and could identify the intensity of hearing loss.

1.3 Objectives

The objectives of the study are:

1. To determine which CAEP components among P1, N1, P2, N2, or P3 has/have the most benefits in assessing the abilities of speech detection and discrimination of the adult SNHL population.

2. To investigate whether changes in the amplitude and latency of these CAEP component occurring with SNHL and hearing aids reflect various stages of auditory processing.

1.4 Significance of Study

This research study could provide useful diagnostic information for clinicians in specific populations in which degree of hearing loss are hard to get (e.g., infants, children, and difficult-to-test individuals). It could also give us a unique opportunity to look into the perception benefits of speech that SNHL patients get from using hearing aids. These electrophysiological measures are associated with the perceptual processes, for instance detection and discrimination of speech that underlie perception. Therefore, they can equip audiologists and clinicians with several useful information concerning the potential benefits of using hearing aids at different levels of brain processing. In addition, it could provide audiologists and clinicians with useful information regarding the ability of the human brain to possible discrimination of the acoustic differences between different speech stimuli better—with aided patients or with unaided patients.

1.5 Scope of Study

This study includes male adults (18–49 years) for both normal and SNHL participants, and is limited to Malaysian Malay population only. This study uses EEG device for data collection and Matlab program for signal processing and analyses. The SNHL participants were of moderately severe to severe cases only.

1.6 Structure of the report

The dissertation consists of 6 chapters including this chapter, which serves as an introduction to the report and discusses the background of study, problem statement, the objectives and the significant of study.

Chapter 2 discusses the literature review and provides details on the topics that are essential for understanding the present study, along with reviews of the previous studies.

In Chapter 3, the discussion is focused on the methodology of the entire project. This chapter elaborates the details about the electroencephalogram (EEG) experiment procedures, data extraction and data processing.

In Chapter 4, the discussion is focused on the results obtained and the statistical analyses of these results. Chapter 5 is then followed which provides an in-depth discussion of the obtained results and finally Chapter 6 describes the conclusion made based on the result obtained.

CHAPTER 2: LITERATURE REVIEW

This chapter provides a brief background on the topics that need to be described to understand the present study along with various review papers of the previous studies done by earlier researchers. The general characteristics of EEG, CAEP signal and its components are presented. A brief description of types of hearing loss and reasons are also discussed.

2.1 EEG

The ionic transfers during the neural activities generate an electrical potential in the brain. This electrical potential can be obtained or measured from different scalp locations. The process of recording this electrical potential is called EEG (Aston, 1990; Sanei & Chambers, 2013; Webster, 2009). The existence of EEG signals in the human was discovered by Hans Berger (1873–1941) and is used in many of the medical and research aspects. Clinicians use EEG to diagnose different types of neural sleep disorders, and behavioural problems. In research, EEG is used in the fields of neuroscience, cognitive psychology, cognitive science, psychophysiological and neuro-linguistics (Boutros, Galderisi, Pogarell, & Riggio, 2011; Schomer & Da Silva, 2012).

EEG signals depend on the brain's physiological states and functional roles (Light et al., 2010). The brain is basically divided into two parts, left and right hemispheres. The left hemisphere is responsible of and controls the right part of the body where it performs the tasks associated with reading, logical thinking, speech and writing, whereas the right hemisphere is responsible of and controls the left part of the body where it performs the activities associated with creative and artistic ability (Sanei & Chambers, 2013). Based on these functionalities, brain was divided into four different lobes as listed in Table 2.1 and illustrated in Figure 2.1.

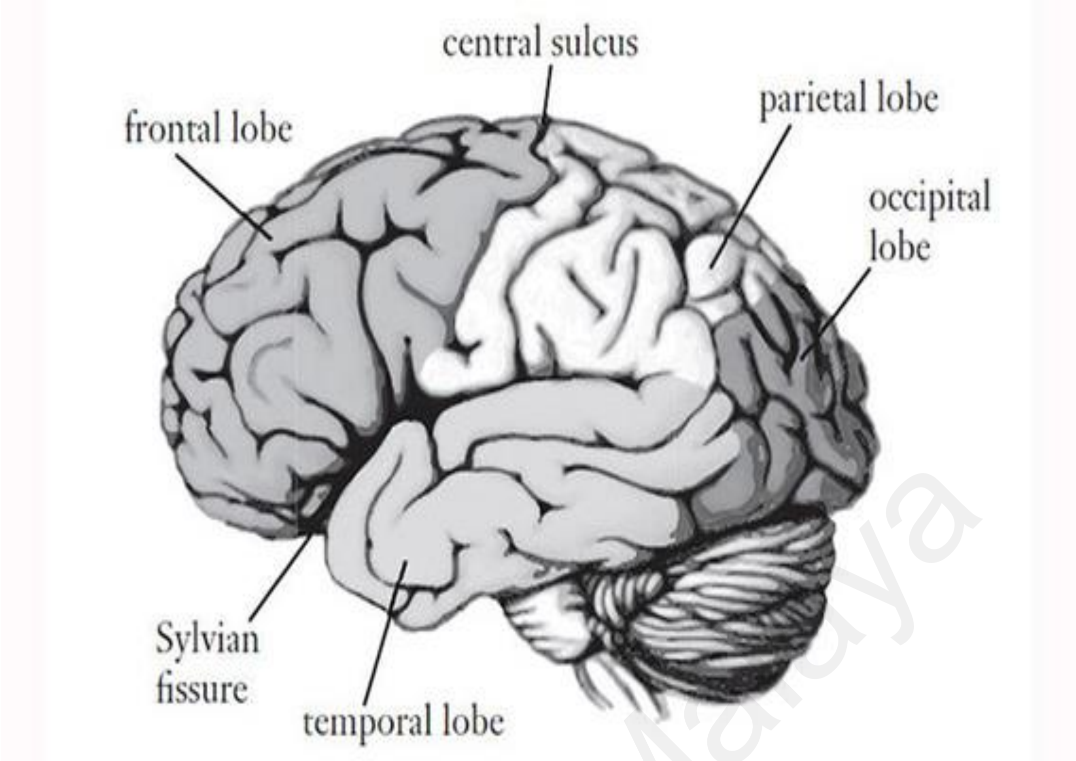

Figure 2.1: The four brain lobes (Kosslyn & Miller, 2015)

Table 2.1: Summary of brain lobe's functional roles

Lobe	Function
Frontal Lobe	- The ability to elaborate thought, behavior and learning: intellect, complex problem solving, planning, judgment, sequencing, and concentration. - Controls responses to emotions, expressive language, word associations, and memory for habits and motor activities.
Parietal Lobe	- Location for visual attention, touch perception, manipulation of objects and goal directed voluntary movements. - Integration of different senses that allows for understanding a single concept.
Temporal Lobe	- Memory acquisition, some visual perceptions, ability to hear, and visual memory. - Classification of objects, intellect. - Sense of identity, behavior and emotions including fear.
Occipital Lobe	- The area of primary visual reception.

EEG measures the electrical potential across the scalp as a function of time. The resulted EEG signal has a very small amplitude that typically varies between 10–100 µV (Niedermeyer & da Silva, 2005). Normally, the EEG signal recorded from the cortex ranges in amplitudes between 500–1500 µV, however, the signal attenuates due to the high impedance between the scalp, skull and brain tissues. Generally, EEG signals appear as a combination of waveforms, and are grouped depending on their:

a. Frequency (speed);
b. Amplitude (power);
c. Spatial distribution (topography);
d. Wave morphology (shape);
e. Reactivity (behavioural state);

The EEG signals obtained during normal rhythmic activities of the brain are classified by their frequency as five different bands including delta (Δ), theta (θ), alpha (α), beta (β), and gamma (γ) (Buzsaki, 2006; Stern, 2005). The beta and alpha waveforms were discovered by Berger in 1929 and he introduces the two terms. Jasper and Andrews (1938) were the first to use the term 'gamma' to refer to the waves higher than 30 Hz frequency. The delta waveform introduced for the first time by Walter (1936) and he assigned all frequencies below the alpha range for this waveform. He then introduced the term theta waveforms as those waves with frequencies in the range of 4–7.5 Hz. The term of a theta waveforms was introduced by Wolter and Dovey in 1944 (Garoosi & Jansen, 2000; Jansen, Agarwal, Hegde, & Boutros, 2003). EEG signals are classified into four bands namely: first are delta activities which vary from 0.5–3.5 Hz. These activities are rare and are sometimes regarded as pathological when noticed in the normal waking adult with high amplitude. Second are theta activities which vary from 3–8 Hz. In the mid of sleep, these activities are often more seen in the temporal areas of the brain. Third are alpha activities which vary from 8–13 Hz. They are found in some areas of the brain especially in occipital region when the person is relaxed with eyes closed. Last are Beta activities which vary from 14–30 Hz. Their amplitudes range from 5–20 µV. They are mostly prominent in some regions of the brain like the frontal and central regions (Aydin, 2008; Liu, Qiu, Chan, Lam, & Poon, 1997) .

Table 2.2 summarizes the frequency range, origin, amplitude and the brain state for each type.

Table 2.2: EEG classification

Band Wave	**Frequency (Hz)**	**Amplitude (µV)**	**Origin**	**Brain state**
Delta, Δ	0 – 4	20 – 200	Cortex	Deep Sleep, infancy and serious organic brain disease.
Theta, θ	4 – 8	10	Parietal and Temporal	Sleep
Alpha, α	8 – 13	20 – 200	Occipital	Relaxing
Beta, β	13 – 30	5 – 10	Parietal and Frontal	Concentration
Gamma, γ	>30	5 – 10	Parietal and Frontal	Memory

2.1.1 EEG Recording

The electrical activities generated in the brain are usually recorded non-invasively from the surface of scalp. Standard electrodes usually consist of flat metal discs made of silver, tin or gold, connected to a wire (as can be seen in Figure 2.2). Electrolyte gel is used as conductive medium between the electrodes and the skin to improve contact and to keep the impedance as low as 10 k (T. Picton et al., 2000).

Figure 2.2: Electrodes and caps used in EEG recording (Boutros et al., 2011)

Whereas the number of electrodes vary from one study to another, they are usually arranged according to the International Standard 10-20 system (JASPER, 1958). Figure 2.3 shows a side and top view of the standard 10-20 electrode system.

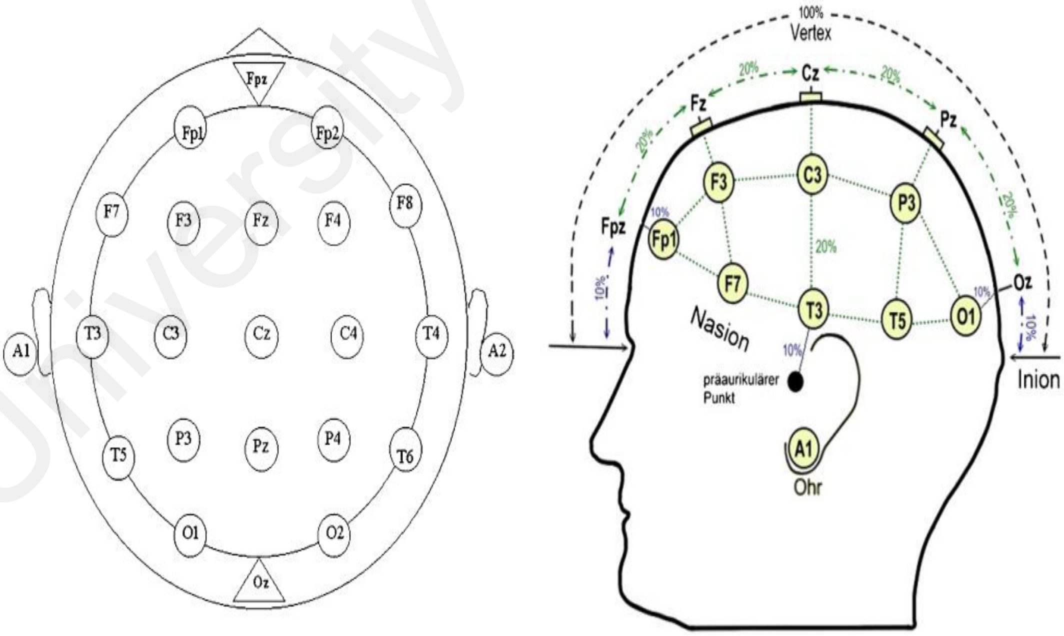

Figure 2.3: The international 10-20 electrode system: side and top views (Milnik, 2009)

Recoding of EEG is done best when it takes place in a quiet, sound proof and shielded environment. The subjects should be seated comfortably in a chair and they should be monitored and observed the whole time of the experiment. Artefacts should be identified and eliminated as much as possible (Rémond, 1976).

In the present project, EEG signals were acquired, stored digitally developed and implemented signal processing algorithms in Matlab for analysis.

2.1.2 Various Artefacts and Their Removal

The amplitude of scalp EEG is usually in the range of 10–100 µV. These low voltage signals are easily subjected to various noise contaminations. These noise contaminations or unwanted signals in the EEG are called the artefacts. They may be of biological origin from the subject or from errors in experimental setup or from surrounding environment. Biological artefacts normally include eye blinking, eye ball movements and muscle movements. Eye blink introduces a very large variation in both amplitude and frequency of the EEG data. Eye ball movement produces distortion in the EEG signal and it may be present even when eyes were closed during EEG acquisition. Muscle artefacts include the limb movement artefacts and facial muscle artefacts.

2.1.2.1 Artefact Removal and Pre-processing Techniques.

Many techniques are available to remove the artefacts present in EEG. The biological artefacts are very hard to remove without losing the EEG data/information during the contamination period or window. The advanced signal processing techniques based on Blind Source Separation (BSS) can be implemented to remove the Eye blink, Electrocardiography (ECG), Electromyography (EMG) and other biological artefacts. Various digital filters can be applied to reduce specific portions of frequency contents to reduce the Power line artefacts, DC drifts, and other band limited biological artefacts such as EEG.

2.1.2.2 DC removal

DC removal can be accomplished using Discrete Fourier Transform where the first term in the series is a DC component. This term is reduced to zero and by performing the inverse DFT, a signal with no DC component may be recovered. DC removal can also be achieved in time domain. Here, the average of the signal over total time is computed and subtracted from the original signal at each time instant to produce no-DC (DC removed) signal.

2.1.2.3 Eye blink, ECG, EMG and other biological artefacts

The movements of the eyes or the muscles in the human body create an electric potential in the brain that can be two orders of magnitude greater than the desired EEG brain activity (Kalpakam & Sahambi, 2004). As this potential propagates through the scalp, it can distort the signal originating from the brain (Fisch & Spehlmann, 1999). These artifacts can be removed using many techniques, including, Independent Component Analysis, Canonical Correlation Analysis and Empirical Mode Decomposition (EMD) which have been used in various previous studies (De Clercq, Vergult, Vanrumste, Van Paesschen, & Van Huffel, 2006; Hyvärinen & Oja, 2000; Kopsinis & McLaughlin, 2009; Van Dun, Wouters, & Moonen, 2007; Wang, Lin, Zhang, Peng, & Zhan, 2013; Zhaojun, Jia, Song, & Baikun, 2006).

2.1.3 Event-Related Potentials (ERPs)

ERP is the potential changes happening in the brain in response to an event/stimuli that occur either internally of externally to the brain. ERP is a better mean to evaluate the activities of the brain as it perceives the stimuli and accordingly makes decisions and controls behavior. ERPs are usually divided into internal (exogenous) and external (endogenous). Exogenous ERPs are evoked by an external stimulus and they are usually found up to 100 ms after stimulus onset. Endogenous ERPs are emitted when the brain makes a decision or initiates a response and they are usually found from 100 ms onward after stimulus onset (T. Picton et al., 2000).

ERPs consist of a series of peaks and troughs. Each peak is described in terms of its polarity and latency. For example, P3 is a positive peak that occurs with 300 ms latency and N2 is a negative peak that occurs with 200 ms latency (Johnson, 1988). Figure 2.4 shows an example of event-related potentials in response to an auditory stimulus.

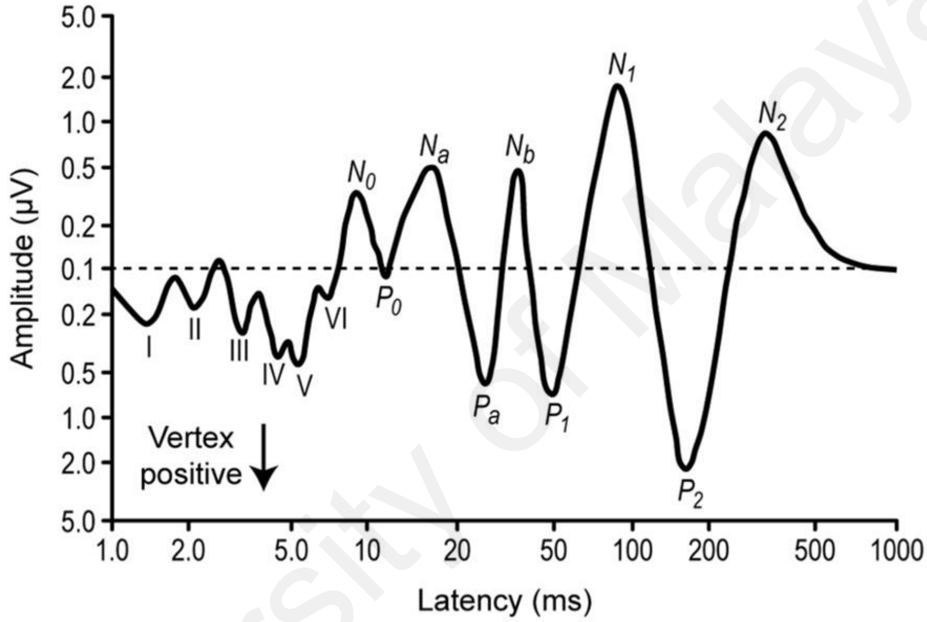

Figure 2.4: Averaged event-related potentials to auditory stimuli (Pérez-González & Malmierca, 2014)

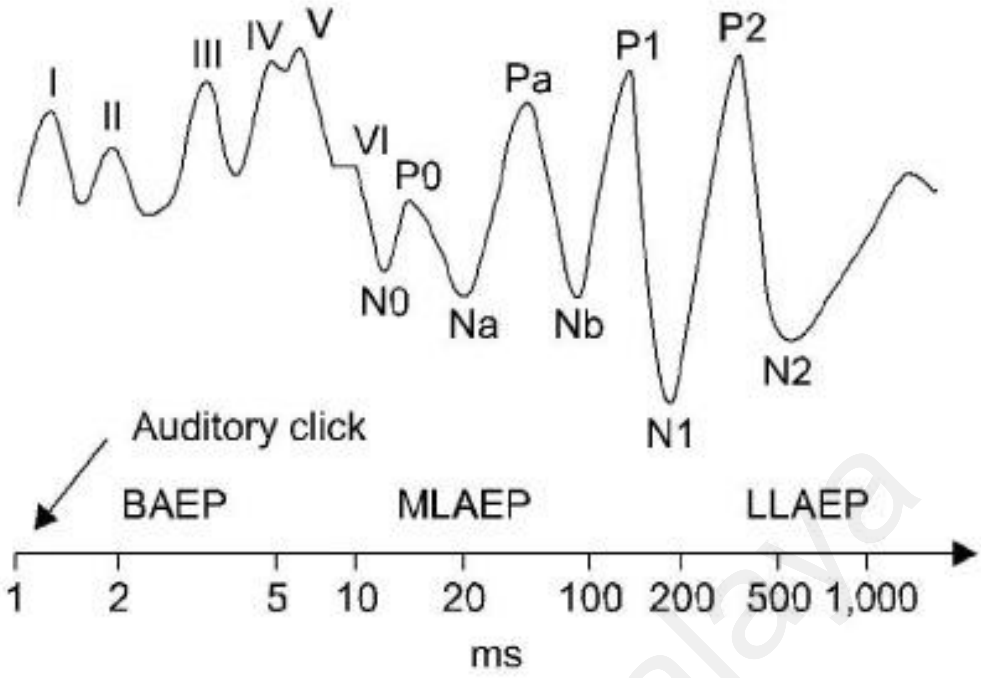

Figure 2.5: The auditory evoked potentials; BAEP=Brain Auditory Event Potential, MLAEP=Medal Latency AEP, LLAEP=Late Latency AEP (Baik, 2007)

2.1.4 CAEP

CAEPs represent summation of the activity of neuron cells in the auditory pathways in response to sounds. Due to the fact that CAEPs could tell us how the brain responses and reacts to sound, they are an ideal tool for examining the brain's auditory function in people. CAEPs have been successfully used to evaluate the brain cognitive processes that are included in the discrimination and detection of complex speech stimuli in normal hearing people. CAEPs are usually classified based on the latency of the signal into: early, middle and late latency responses. Early-latency responses are always elicited between 1–10 ms after the onset of the stimuli followed by 10–50 ms of Middle-Latency Responses (MLRs) and later latency responses as > 50 ms (Alain, Roye, & Arnott, 2013; T. Picton et al., 2000). While early and middle latency responses involve no cognitive processes, late responses involve neural processes such as discrimination of pure tones that vary in frequency or complex signals such as speech.

CAEPs are best recorded when the participant is awake. The participants are always asked to minimize their movements and to sit still so that muscular noises are avoided.

2.1.4.1 Early-latency responses

Early-latency responses or Brainstem Auditory Evoked Response (BAER) are very small auditory brain potentials, about 0.5 μV in amplitude, that represent electrical events of the brainstem auditory pathways and are elicited by auditory stimuli. BAEPs are made up of different waves numbered from I–VI (see Figure 2.4 and 2.5) that extend to 10 ms after stimulus and each wave is associated to physiological generators (Berger & Blum, 2007; Woldorff & Hillyard, 1991). These waves are less relevant to this work and are discussed briefly only.

2.1.4.2 Middle-latency responses

MRLs are electrical brain waves that occur between 10–80 ms after the onset of auditory stimuli (Amenedo & Díaz, 1998; Borgmann, Roß, Draganova, & Pantev, 2001). MLR recording is either evoked by the usage of a single recording or multiple recording channels. during the recording session in normal adults using click stimuli, at electrodes in frontal midline (Fz and Cz), components of MLR waveform will in most cases show certain latency values: Pa (~30 ms), Pb (~50 – 70 ms), Na (latency: ~19 ms), and Nb (~40 ms) (Yvert, Crouzeix, Bertrand, Seither-Preisler, & Pantev, 2001) as shown in Figure 2.4 and 2.5. MLRs is sometimes used as an assessment of the three hearing loss types (Vivion, Goldstein, Wolf, & McFarland, 1977). In case the response is evoked with tonal stimuli from someone who has with low degree hearing loss (mild), recordings should reflect the hearing loss’s degree. Interesting results were found when Researchers employed MLRs in those with cortical pathologies. researchers have once showed that MLRs components are not elicited nor have a reduction in amplitude when it was recorded from people who had a lesion in the primary auditory cortex (Kileny, Paccioretti, & Wilson, 1987). However, individuals with lesions in either the medial geniculate body, auditory association areas, or frontal or parietal operculum areas—MLRs were not affected (Swink, 2010).

2.1.4.3 Long-latency auditory evoked potentials

LAEPs are a set of event-related potentials that occurr between 50–600 ms after stimulus onset. LAEPs are elicited by wide range of auditory stimuli clicks, pure tones, noise bursts, as well as musical, environmental sounds, and speech sounds (Alain et al., 2013). LAEPs potentials, like ERPs, consist of a series of peaks and troughs. Each peak and trough is described in terms of its polarity and latency as can be seen in Figure 2.4 and 2.5. LAEPs are generated by different brain locations including primary and association areas of each auditory cortex, thalamocortical projections, the parietal cortex, and the prefrontal cortex (T. Picton et al., 1999).

In adults, LAEPs is dominated by a well-defined positive peak, P1, that is typically located between 50–80 ms after the onset of the stimulus (Julia Louise Wunderlich & Cone-Wesson, 2006). This is followed by a negative peak, N1, which occurs between 90–150 ms post-stimulus onset. N1 is then followed by a positive peak, P2, which has latency between 175–200 ms. These 3 peaks are usually studied together in what is called P1-N1-P2 complex. it was first introduced in 1939 by Pauline Davis and was the first components of CAEP to be ever recorded (Hall, 2007). The P1-N1-P2 complex is regarded as an obligatory response, which means that the three components are basically by the characteristics of the stimulus and not the perception of the auditory cues of the brain. The said response is said to reflect representation of speech in the central auditory system of the brain independently of listener attention (Boothroyd, 1984; B. A. Martin, A. Sigal, D. Kurtzberg, & D. R. Stapells, 1997; A. Sharma & Dorman, 1999). The amplitude and latency of the P1-N1-P2 complex is sensitive to various parameters and changes in the stimulus variables including inter-stimulus interval (ISI), frequency, duration, rise time, stimulus complexity and intensity (Alain, L. Woods, & Covarrubias, 1997; Jodi M. Ostroff, McDonald, Schneider, & Alain, 2003; Roberts, Ferrari, Stufflebeam, & Poeppel, 2000; Woods, Alain, Covarrubias, & Zaidel, 1993). This sensitivity makes the P1-N1-P2 complex an excellent tool for examining the physiological detection of important acoustic cues contained within a signal. They could be used to evaluate the ability of the auditory cortex of the brain to detect acoustic changes within speech sounds or stimuli (Martin & Boothroyd, 1999). N1 is usually the largest among the three waves (Alain et al., 2013).

The P1-N1-P2 complex is followed by the negative peak, N2, at 200–250 ms from the stimulus onset. The N2 peak is not always found in adults' CAEP (Purdy, Kelly, & Thorne, 2001). N2 component is then followed by a positive deflection at midline parietal site called P3 or P3b. P3 is a large positive component that usually occurs between 220–380 ms and is most commonly elicited by oddball paradigm. P3 is generated in different areas in the brain including the auditory cortex. N2 and P3 waves are called later cognitive CAEP. They could be used by audiologists to provide information concerning the ability of the brain to discriminate or differentiate between the acoustic differences between speech stimuli as they provide information on higher-order processing of sensory stimuli needed for sound discrimination (Donchin, Ritter, & McCallum, 1978; Stapells, 2002). Table 2.3 summarizes some of the reviews that discussed the CAEP components.

Table 2.3: Summary of different CAEP components study

Authors	Title	Year	Components	Aim
Duncan, Connie C. Barry, Robert J. Näätänen, Risto Polich, John Reinvang, Ivar Van Petten, Cyma	Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria.	2009	MMN, P3, N400	Guidelines on how to elicit, record, and quantify these components in cognitive studies.
Bharath, Srikala Gangadhar, B. N. Janakiramaiah, N.	P300 in family studies of schizophrenia: review and critique.	2000	P3	To discuss how subject samples are defined, the needed sample size, ERP methodology, and the relationship of P300 measures to neuropsychological test outcomes.
Johnson, R	The amplitude of the P300 component of the event-related potential: review and synthesis.	1988	P3	To discuss the factors affecting the occurrence and magnitude of P3.
Picton, TW Bentin, S…et al.	Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria.	2000	All	Reviewing the standard recording and publication criteria (like enhancing and averaging)
Näätänen, Risto Picton, Terence	The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component	1987	N1	To discuss the structure of N1.

Table 2.3 continued

Näätänen and Gaillard	The Orienting Reflex and the N2 Deflection of the Event-Related Potential (ERP)	1983	N2	To discuss the characteristics of N2 components including the morphology, topography, association with other components, stimuli, magnitude … etc.
Kate Crowley Ian M Colrain	A review of the evidence for P2 being an independent component process: age, sleep and modality	2004	P2	To describe the evidence of P2 as an independent component.
Julia Louise Wunderlicha , Barbara Katherine Cone-Wessonb	Maturation of CAEP in infants and children: A review	2006	P1, N1, P2, and N2	Focuses on the Maturation CAEP morphology, changes in the scalp topography of the components

2.2 Hearing

The hearing system (shown in Figure 2.6) comprises of auditory sensory organs: outer ear, middle ear, inner ear, auditory pathways and brain lobes that receive, analyse, and interpret information pertaining to sound (Tortora & Derrickson, 2012; Viola, Thorne, Bleeck, Eyles, & Debener, 2011). Through language, humans are able to understand the world, organize his universe, understand others, make abstractions and convey thoughts and feelings, acquire knowledge and interact with the surroundings. Therefore, the more sound stimuli we receive, the more prepared we are to interact and deal with other individuals.

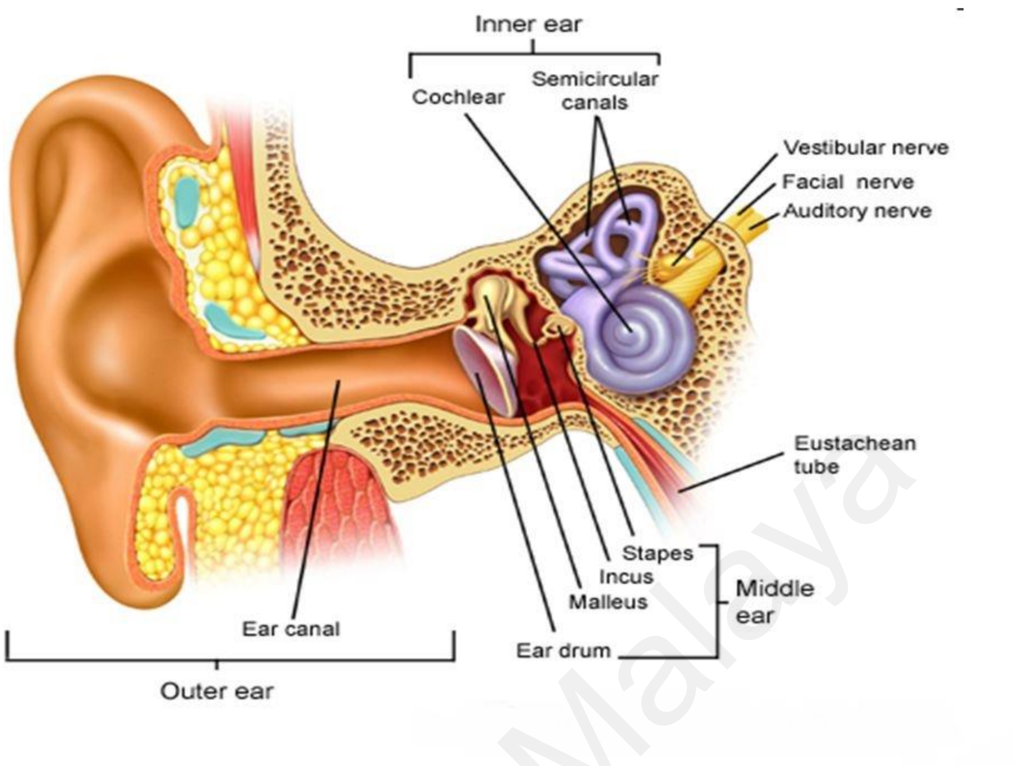

Figure 2.6: Anatomy of the human ear (Courtesy: Viola, Thorne, Bleeck, Eyles, & Debener, 2011)

However, the human auditory system is always vulnerable and the impact of hearing loss is huge. It can affect not only the ability to understand and perceive information transferred through sound but also the way in which a person may relate with his/her environment and culture. As a result, hearing loss is significant and may have different effects including biological, psychological, and social effects.

2.2.1 Hearing Loss

Hearing loss is known as the averaged hearing impairment at 1000, 2000 and 4000 Hz, which is measured by a test known as pure tone audiometry. In another words, people who have a hearing loss diminished their ability to hear sounds like other people do. Hearing loss with high frequency has to be taken seriously into account, due to this degree of hearing loss, speech conception and comprehension is distorted in noisy environments. Individuals who are intellectually disable or intellectually impaired

(Brain Injury, learning problems, depression, Tinnitus, Schizophrenia, Consciousness, cochlear damage, aging) are usually exposed to loud noise levels in homes, day-care centres and many other places too. Hearing loss is regarded to be present when the degree of hearing loss is more than 25 dB at the one ear or both as per standard definition (see Table 2.4 for the classification of degree of hearing).

Therefore, hearing loss with mild levels could lead to severe handicap, in case they happen in individuals who are intellectually disable or intellectually impaired with comparison to normal healthy people. People who have intellectual disability of high level, aside from hearing loss problem, other aspects may affect decisions of intervention, like functions of pre-speech, the level of noise in home or day-care centre and insecurity feeling. When clinicians and audiologists describes hearing loss, they usually look at three hearing loss aspects, namely: type, degree, and configuration (reasons) that caused hearing loss.

By definition, audiology is the science of hearing (Hood, 1998). In the last three decades, audiology has been evolving as an academic field of study, along with its role in clinical profession. The science of audiology involves the identification and diagnosis of any hearing impairment and equally important, the prevention and management of the hearing impairments. According to Katz, Gabbay, Ungerleider, & Wilde (1978), the main goal of a diagnostic procedure is to successfully rehabilitate of auditory impaired people.

2.2.2 Types of Hearing Loss:

Audiologists divide hearing loss into three types. The first type is called Conductive hearing loss which happens when there is difficulty in transmitting sound from the outer part of the ear (canal) to the middle part (eardrum) and then to the three tiny bones (ossicles) of the middle ear. Therefore, it causes sounds to be softer and more difficult to hear. This type is corrected either by medical intervention or surgical intervention. There are many causes of conductive hearing loss, including:

1. Fluid found near to the eardrum due to colds or allergies
2. Infection of the ear (otitis media)
3. Poor function of eustachian tube
4. Too much earwax (cerumen)
5. Hole in the eardrum
6. Foreign body in the ear canal
7. Swimmer's ear (external otitis)
8. Malformation of the outer ear, ear canal, or middle ear.

SNHL is the second type and it happens when there is harm and deficits in either the inner part of the ear (cochlea) or in the auditory nerve pathways leading to auditory cortex. In most of cases, it is difficult to correct SNHL and it is therefore the most common cause of permanent hearing loss. SNHL decreases the capability of hearing faint sounds. Even though the sound is loud enough to hear, therefore sound may still be unclear or get muffled. There are many causes of SNHL including:

1. Toxic drugs to hearing
2. Aging.
3. Genetic or hereditary
4. Head injury or trauma
5. Deficits and Malformation of the inner ear
6. Exposure to loud sounds or noises

The third type is known as mixed hearing impairment and it is a summation of both SNHL and conductive hearing loss. Meaning that, there could be harm or deficits in the outer or middle ear and in the inner ear (cochlea) or the nerves of the auditory pathway. Figure 2.7 shows the types of hearing loss.

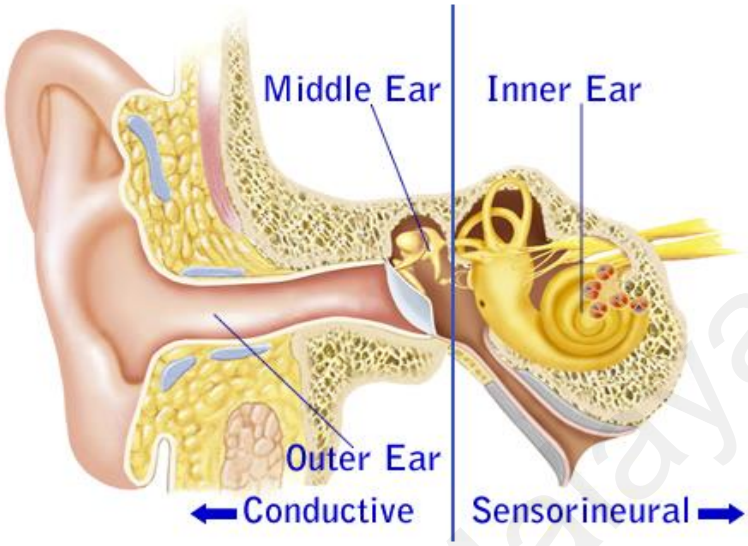

Figure 2.7: Types of Hearing Loss ("Types of Hearing Loss," 2016)

2.2.3 Degree of Hearing Loss

Hearing loss is also divided into different degree which refers to the intensity or the severity of hearing damage. Table 2.4 shows one of the most known classifications of hearing loss. The numbers represents the range of the patient's hearing loss in decibels (dB) (Clark, 1981).

Table 2.4: The classification of degree of hearing in dB

Degree	Range (dB)
Normal	–10 to 15
Slight	16 to 25
Mild	26 to 40
Moderate	41 to 55
Moderately severe	56 to 70
Severe	71 to 90
Profound	91+

2.3 Related Works

In general, there have been some studies where the combined effects of SNHL and hearing aids on CAEPs were investigated. In a very early study, Rapin & Graziani (1967) showed that the majority 5/8 of their 5–24 months old infants with severe to profound sensorineural hearing loss had aided CAEP thresholds to clicks and tones that were at least 20 dB lower compared to their unaided thresholds. Another significant data found by Rapin and her colleagues that there is an increase on CAEP amplitudes with use of hearing aid (Isabelle Rapin & Leonard J Graziani, 1967). Recent studies also showed that the degree of hearing loss changed the amplitudes and latencies of CAEP components differently, where it was found that the CAEP amplitudes varied considerably than the CAEP latencies in people both, with normal and with hearing loss (P. A. Korczak, Kurtzberg, & Stapells, 2005; Oates, Kurtzberg, & Stapells, 2002). A group of scientists delivered a 1 kHz tone to 13 young adults with normal-hearing at 7 different stimulus levels, both with hearing aids (20 dB amplification) and without hearing aids, where there was no significant effect of amplification on CAEP amplitudes. However, significant latency delay was found in people who are using hearing aids (Billings, Tremblay, Souza, & Binns, 2007).

In contrast with some literature which used normal-hearing people in their studies, tests were done on 14 subjects with a hearing disability to assess the detection of CAEP's components using two sounds at two different dB levels (/ba/ and /da/): at 65 dB and at 80 dB. It was shown that the usage of hearing aids over time substantially improved CAEP results, i.e. an increase in the amplitude of CAEP and a decrease in its latencies. The results showed a difference between hearing loss's degrees. For moderately to severely hearing-loss participants, participant with hearing aids had an effect on presence of the response at the lower stimulus intensity only. However, in the severe-profound hearing loss participants, the impact was due to the higher stimulus intensities only. Hence, amplification effects (i.e., differences between participants with hearing aids and without hearing aids) were more possibly to happen near threshold than at supra-threshold levels. The study concluded that CAEPs may be used to evaluate the benefits that individuals with SNHL are getting from their personal hearing aid(s) and that further research is required to determine which components of CAEP among P1, N1, P2, N2, or P3 are most beneficial in assessing the abilities of adult SNHL population to detect and discriminate speech sounds (P. A. Korczak et al., 2005). In a different study, Alessandra and colleagues analyzed the presence of CAEPs while 22 adults with hearing loss (with and without amplification) listened to speech sounds of low (/m/), medium (/g/) and high (/t/) frequencies. The results showed increase presence of CAEP responses with the hearing aids (Durante et al., 2014).

Thus, the main purpose of this study was to investigate which CAEP components (P1, N1, P2, N2, or P3) are most beneficial in assessing the abilities of adult SNHL population to detect and discriminate speech sounds. The literature review done related to this study is summarized in Table 2.5.

Table 2.5: Summary of related works

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 were recorded from 10 adults, 5 females, and 5 males, using speech vowels	CAEPs were different in response to high-frequency energy compared to lower-frequency energy. notable impacts because of duration of stimulus were also seen, with longer stimuli duration showed low amplitudes than shorter stimuli duration

Table 2.5 continued

P300 in subjects with hearing loss	Ana Cláudia Mirândola Barbosa Reis	2006	29 subjects, 15 of them are male and 14 are female, with ages between 11 to 42 years, were evaluated with severe to profound SNHL	P300 component was only observed in 17 out of the 29 subjects. Mean amplitude and latency were 326.97 ms and 3.76 V, respectively. They concluded that P300 can be recorded in subjects with hearing loss.
Aided Cortical Auditory Evoked Potentials In Response To Changes In Hearing Aid Gain	Curtis J. Billingsa, Kelly L. Tremblay, and Christi W. Miller	2011	Evoked potentials were recorded from 9 normal-hearing adults in both unaided and aided conditions. In the aided case, a 40-dB audio signal was delivered to a program to provide 4 different gains (0, 10, 20, and 30 dB).	The results showed that smaller amplitude and delayed latencies of the Aided CAEPs in comparison to unaided CAEPs, this was probably due to the increases of noise levels caused by the hearing aid.
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	2000	12 control subjects with normal hearing were tested with tone bursts stimuli in the range (400/440, 1500/1650, and 3000/3300 Hz), words (/bab/vs /dad/) and CVs (/ba/ vs /da/)	Tone bursts results showed MMN in 46%–71% of tests but for only 25%–32% of speech contrasts. However the magnitude of N1 and MMN for tones bursts were nearly related, and both reflect the auditory cortex tonotopicity.

Table 2.5 continued

Middle and late latency ERP components discriminate between adults, typical children, and children with sensory processing disorders	Patricia L. Davies1, Wen-Pin Chang2 and William J. Gavin	2010	3 different groups; first 18 adults (20–55 years), and then 25 typical children (5–10 years) and finally 28 children with sensory processing disorders (between 5–12 years). Recordings were in response to two stimuli (1 and 3 kHz) with two intensities (50 and 70 dB).	Amplitude and latency of the CAEP were acquired from the averaged signal for each analysis of stimuli Discriminant showed two functions, one outlined the relationship of the CAEPs on deficit continuum of sensory processing disorders and one outlined the relationship of CAEPs on a developmental continuum.
Effects of Various Articulatory Features of Speech on Cortical Event-Related Potentials and Behavioral Measures of Speech-Sound Processing	Peggy A. Korczak, and David R. Stapells	2010	CAEPs were acquired from 20 adults with normal-hearing in response to 3 sets of speech stimuli CV (/bi versus /bu/, /ba/ versus /da/, /da/ versus /ta/) delivered at 65 and 80 dB.	Mean amplitudes for all CAEPs were higher because of the vowel contrast compared to the two consonant contrasts. Likewise, the mean latencies of MMN, P3b, and RT were notably shorter for the results due to the vowel versus consonant contrasts.

Table 2.5 continued

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 recorded to two consonant vowels /ba/ and /da/ stimuli delivered at two levels (65 and 80 dB) from 20 adults with normal-hearing and 14 SNHL adults	Hearing aids usage enhanced the detectability of all the components of the CAEPs and performance of behavioral d-prime scores at both intensities.
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	13 normal-hearing young adults were presented with 1 kHz tone delivered at 7 different stimulus levels, both with hearing aids (20 dB amplification) and without hearing aids	The CAEP amplitude showed no significant effect of amplification. However, significant latency delay when aiding was found
Objective Assessment of Speech in Noise Abilities and The Effect of Amplitude in Children with Hearing Loss	Smantha Gustafon, Alexandra P. Key, Benjamin W.Y. Hornsby and Fred H. Bess	2008	Syllable /gi/ and /gu/ to condition	Similar processes between CNHL and CHL while listening at loud presentation levels without hearing aids
Formal Auditory Training in Adult Hearing Aid Users	Daniela Gil and Maria Cecilia Martinelli Iorio	2010	Verbal sounds with syllables /Pa/, /Ta/, /Ca/ and /Fa/ -Non-verbal sounds - Sound	Elderly Group had significantly better performance compared to control group in the assessments after auditory training

Table 2.5 continued

Late Auditory Evoked Potential in Elderly Long-Term Hearing Aid Users with Unilateral or Bilateral Fittings	Sibylle Bertoli, Rudolf Probst and Daniel Bodmer	2011	0.51 and 2 kHz pure tones	No significant differ was found for the responses of the hearing-aid users for any of the components P1, N1 or P2 between the aided and unaided ears, but a significant interaction for P2 amplitudes was found between ear and frequency.
Cortical Auditory Evoked Potential: evaluation of speech detection in adult hearing aid users	Alessandra Spada Durante Margarita Bernal Wieselberg Sheila Carvalho Nayara Costa	2014	CAEPs were recorded from 22 adults with moderate to severe SNHL in response to Speech sounds (/m/), (/g/) and (/t/) with intensities of 75, 65 and of 55 dB	Results showed that hearing aids increased the presence of CAEP
Cortical Auditory Evoked Potentials in Children with a Hearing Loss: A Pilot Study	Amineh Koravand, Beniot Jutras and Maryse Lassonde	2012	Verbal /ba/ and /da/, non-verbal and 1 kHz pure tone wide-band noise	Larger P1 amplitude and high reduction in N1 latency and amplitude in non-control group compared to control

CHAPTER 3: METHODOLOGY

In this chapter, the methods used for CAEP data collection and analysis are described.

3.1 Participant / Subjects

CAEPs were recorded from two groups of participants. An adult control group consisting of 12 right-handed Malay male volunteers aged between 20 to 30 years (mean age = 23.5) having tested normal hearing and confirmed by PTA measurement (see Appendix A for a sample PTA test). Subjects showed normal audiological presentation in both ears (air conduction thresholds 20 dB hearing level from 125–4000 Hz bilaterally, 40 dB HL at 6000 and 8000 Hz, and pure-tone averages (PTA; average from 500–4000 Hz) 15 dB HL) (Brant & Fozard, 1990). The participants recruited were Undergraduate students of Faculty of Engineering, University of Malaya (UM). The second group consists of 10 right-handed Malay male adults with SNHL between 15 to 49 years (mean age = 39.1) who were recruited from the local community through department of Otorhinolaryngology (ENT), UMMC hospital, Kuala Lumpur. Those adults had bilateral hearing loss, with moderately severe to severe hearing loss (between 56–90 dB), and wearing bilateral hearing aids of more than 1 year. Participants' details are shown in Table 3.1 below and a graphical depict of the two group is shown in Figure 3.1. All participants signed a consent form prior to participation in experiment (refer to Appendix C for a sample of the consent form). A Mental State Examination (MMSE) test was also conducted prior to the experiment to evaluate the participants' mental abilities, memory capabilities, attention and language deficiency (Folstein, Folstein, & McHugh, 1975). All participants showed no cognitive impairments as the score of the MMSE was always higher than 24/30 for each participant (see Appendix D for MMSE test details). The study was approved by the Ethical Committee of the University of

Malaya. The difference in mean age between the control group and the SNHL group does not affect the results as adults are considered between 18 to 49 years old and both groups here fall into that category.

Table 3.1: Subjects details

Subject	No. of sub.	Age (Mean)	Gender	Severity
Control	12	20-30 (23.5)	M	Normal
SNHL	10	15-49 (39.1)	M	Moderately severe to severe

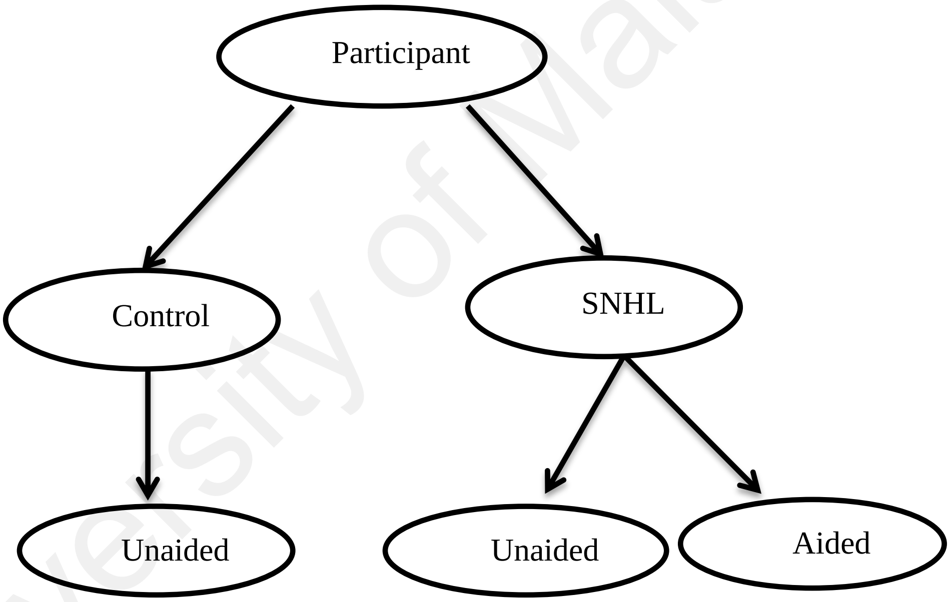

Figure 3.1: The three cases or groups used in this study (Control, unaided SNHL and aided SNHL)

3.2 Stimuli

Naturally produced CVs (/ba/ and /da/) were used in this study. Although there are many auditory stimuli that can evoke CAEPs responses (e.g., tones, clicks and noise bands), naturally produced speech stimuli were chosen for this study due to the fact that they represent high complex signals that are poorly approximated by non-speech stimuli. This feature makes speech stimuli able to elicit a more robust waveform and enjoy a special and distinct mode of perception (Dorman, 1974; Tremblay, Friesen, Martin, & Wright, 2003). These specific CV syllables were selected due to a number of reasons. First, the high contrast between the consonant and the following vowel makes them stronger stimuli. Furthermore, these stimuli differ with place of articulation, an articulatory feature of speech that is particularly vulnerable to the effects of peripheral hearing impairment. The speech confusion, in hearing loss people, happens mainly between stop consonants that differ with place of articulation. This means that Acoustic cues that signal place of articulation appear to be particularly vulnerable when auditory processing breaks down (Nina Kraus, McGee, Carrell, & Sharma, 1995; Oates et al., 2002; Raz & Noffsinger, 1985). Finally, the CVs were also chosen so that comparisons can be made with other studies that used these same stimuli (P. A. Korczak et al., 2005).

The stimuli were presented at 80 dB sound pressure level (Association, 2005; Dehaene-Lambertz & Baillet, 1998; Peggy A Korczak & Stapells, 2010; Ladefoged & Maddieson, 1998; Julia L Wunderlich & Cone-Wesson, 2001). It was tested with each subject that this sound was at a loud but comfortable listening level. The /ba/ and /da/ CVs were characterized by their contrasting voiced/voiceless articulatory features of speech. The speech stimuli were recorded at 44100 Hz sampling rate from the natural speech produced by a female Malay speaker using Sony IC recorder (ICD-UX513F). The CVs were 300 ms in duration each and were delivered monaurally via Sennheiser HD 428 headphones to both ears. The stimuli presented were calibrated at ear level using Optimus sound level meter to obtain the desired sound pressure level (80 dB). Stimuli type and duration used in previous studies varied widely and not all stimuli are suitable for recording CAEPs. For example, CAEPs can be recorded on different auditory stimuli including simple tones, CVs, words, and even full sentences. However, several studies have indicated that the recording of CAEPs on speech stimuli provides better insights into late cognitive processes in the brain. Meanwhile, tones provide better insights to early ERPs and are optimal for ABR recording (P. A. Korczak et al., 2005;

Stelmachowicz, Lewis, Seewald, & Hawkins, 1990). The work of Picton, Alain, Otten, Ritter, & Achim (2000) recommended that naturally produced speech stimuli should be used for CAEPs research, since the aim is to apply the results to speech perception in everyday life. Different durations of speech stimuli were used in many literatures, ranging from 90–600 ms (Obleser, Eulitz, Lahiri, & Elbert, 2001; Anu Sharma, Kraus, J. McGee, & Nicol, 1997). The duration for naturally produced speech stimuli can vary widely, from 300 ms (Jodi M Ostroff, Martin, & Boothroyd, 1998) to 756 ms (Tremblay et al., 2003). However, there seems to be no agreement in the literature concerning optimal stimulus durations for speech-evoked CAEP recordings.

Stimuli were presented with a pseudo-randomized oddball sequence of 80% standard and 20% deviant presentations with inter-stimulus interval (ISI) of 800±500 ms and delivered monaurally via headphones to both ears. The CV stimuli were tested for two runs. Each run consisted of 350 stimuli, i.e. 70 deviant stimuli and 280 standard stimuli. Thus, there were 140 deviant stimuli and 560 standard stimuli presented over the two runs. The order in which the stimuli where presented ensured that there was 3–5 standard stimuli between each deviant stimulus. There was no counterbalance for this study; that is, the (/da/) stimulus was always the standard and the (/ba/) stimulus was always the deviant. Figure 3.2 shows how one sequence of the oddball paradigm was delivered to the participant.

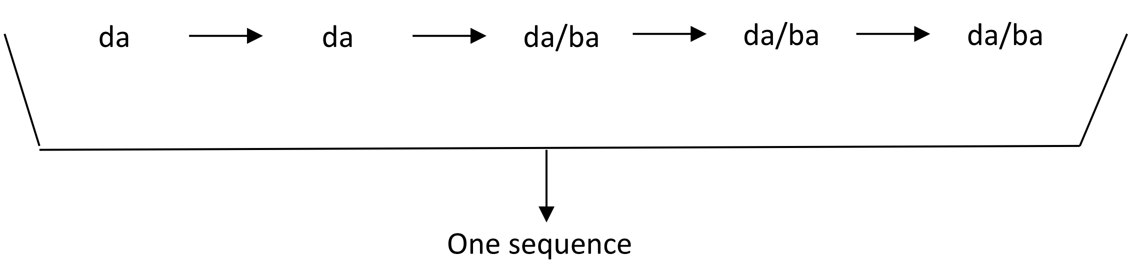

Figure 3.2: A sequence of the oddball paradigm used in this study

The control group's participants were tested only in the condition were they don't wear hearing aids and the SNHL group's participants were tested in two cases, while wearing hearing aids once and without hearing aids another. Figure 3.1 show a graphical depiction for the two conditions.

3.3 CAEP Recording

Subjects were seated in a comfortable armchair in a sound-proof chamber. They were instructed to ignore the stimuli and minimize their eye blinks and muscle movements. Recording was done twice with approximately 35 minutes duration each. To ensure continuation of passive listening condition, written short stories were presented throughout the experiment. Recording was done at 500 Hz sampling rate using the commercially available Enobio EEG data acquisition system. Data were recorded using 8 Ag/AgCl electrodes mounted on Neoprene EEG cap located over the scalp sites Fz, Cz, Pz, FPZ, F7, C3, P7 and F7 (according to the modified International 10–20 System) (Lee, Jaw, Pan, Lin, & Young, 2007). EEG activity from each electrode was measured with one active electrode called Common Mode Sense (CMS) and one passive electrode, Driven Right Leg (DRL) linked to the right mastoid. Figure 3.4 shows the electrode sites used in this study.

Figure 3.3: Electrodes' positions used in this study highlighted by the green color

3.4 CAEP Waveform and Component Analysis

After the collection of the data, the responses evoked by the standard and deviant stimuli were processed offline (e.g., correction of the baseline drift, removing the power line frequency and digital filtering). These were done using notch filter at 50 Hz and Butterworth band-pass filter in the frequency of 1–49 Hz. The evoked responses were then averaged separately for each stimulus. All standard and deviant evoked responses were initially de-noised by the EMD technique (Kopsinis & McLaughlin, 2009; Wang et al., 2013) and inspected visually. Figure 3.5 summarizes the flow chart of steps used in the analysis process:

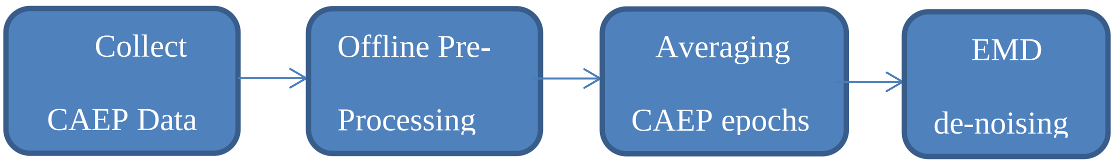

Figure 3.4: Summary of the steps used in the analysis process

In brief, EMD was introduced for the first time by Huang (Huang et al., 1998). EMD has been recently used in filtering and de-noising nonstationary and nonlinear data. It fundamentally breaks down data into a number of amplitude and frequency elements. These elements are referred as intrinsic mode functions (IMFs) in which valuable information and artifacts or noises are reserved more or less separately. One important advantage of this technique is that it can handle non-stationary signals (e.g., EEG) and/or those generated by a nonlinear system (Wang et al., 2013).

The criteria used to determine presence or absence of CAEP response were: (1) using visual inspection where the CAEP is present if individual CAEP peak was larger than the level of the pre-stimulus baseline; and then (2) using statistical methods where correlation coefficient test and t-test were used to compared a typical standard CAEP waveform, used by previous studies, with individual subjects' responses and those response that had maximum correlation coefficient (r) and ($p < 0.05$) were considered present (this criterion was done only for the control subjects data). CAEP analysis included baseline-to-peak amplitude and latency comparison with a typical standard CAEP waveform described by (Näätänen, 1992) where N1 & N2 were defined as the most negative peak occurring 80–150 ms and 180–250 ms after stimulus onset, respectively. P1, P2 &P3 were also defined as the most positive peak between 55–80 ms, 145– 80 ms and 220–380 ms, respectively. In some trials, P1 & P2 were below the baseline, i.e., a negative value, in which case the latency of the peak was measured and the amplitude was recorded as missing. All measurements reported here are from responses recorded at Cz electrode since it was at this electrode the CAEP was at its largest.

The correlation coefficient test and t-test were done in two stages. Firstly, it was done between individual subjects' CAEP responses and the typical standard CAEP. The waveform with maximum correlation coefficient (r) to the standard waveform was then selected as the standard waveform. Secondly, the selected waveform was then used for comparison purposes between the rest of the individual subjects' responses. Waveforms with maximum correlation coefficient (r) and have ($p < 0.05$) were accepted and those with low correlation coefficient (r) were neglected. It should be noted that 2 out of 12 subjects' data had low correlation value and were neglected. Therefore, only 10 control subjects were used in the analysis of the control subjects.

After each subject's data was processed individually, the mean and standard deviation of the peak-to-peak amplitudes and latencies of the P1, N1, P2, N2, and P3 components for all subjects of the three groups (Control, unaided SNHL and aided SNHL) were calculated separately for each stimulus for the purpose of easing the statistical analysis. The mean latency and amplitude measures for the CAEPs of the three groups were then analyzed separately using one-way ANOVA test. The test was done on the electrode that showed the maximum responses (Cz). The differences were only considered significant at a level of $p < 0.05$. The mean latency and amplitude measures for the CAEP's components of the unaided and aided conditions for SNHL participants for both stimuli were also analyzed separately using t-test. This was done to show if there are any differences between each stimulus. The differences were only considered significant at the level of $p < 0.05$.

The mean latency and amplitude measures for the CAEP's components of the unaided and aided conditions for SNHL subjects were subtracted from each other to find the gain of the mean amplitude and latency in which the subjects acquired from their hearing aids. This was done separately for each individual.

CHAPTER 4: RESULT

The results obtained from the CAEP experiments are provided in this chapter, which is organized as follows.

4.1 EMD

As mentioned in the methodology, the averaged responses were initially de-noised by EMD technique. A sample of the cleaned responses is shown in Figure 4.1.

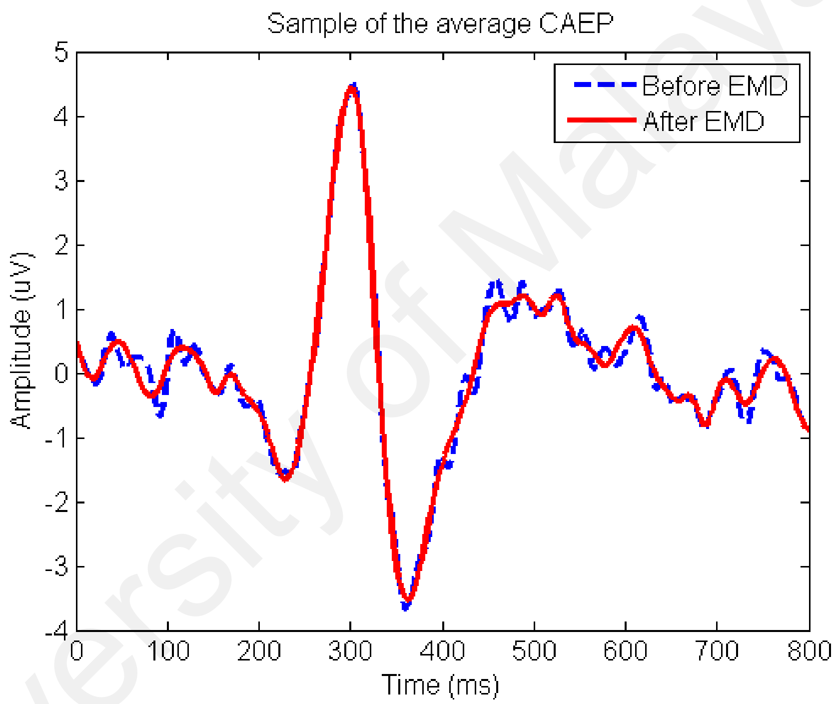

Figure 4.1: CAEP waveform recorded before and after EMD de-noising process. The blue dashed line is before EMD de-noising. The red line is the cleaned CAEP waveform.

4.2 Subject Results

A sample of the average CAEP waveforms for the control and SNHL subjects for both stimuli is shown in Figure 4.2.

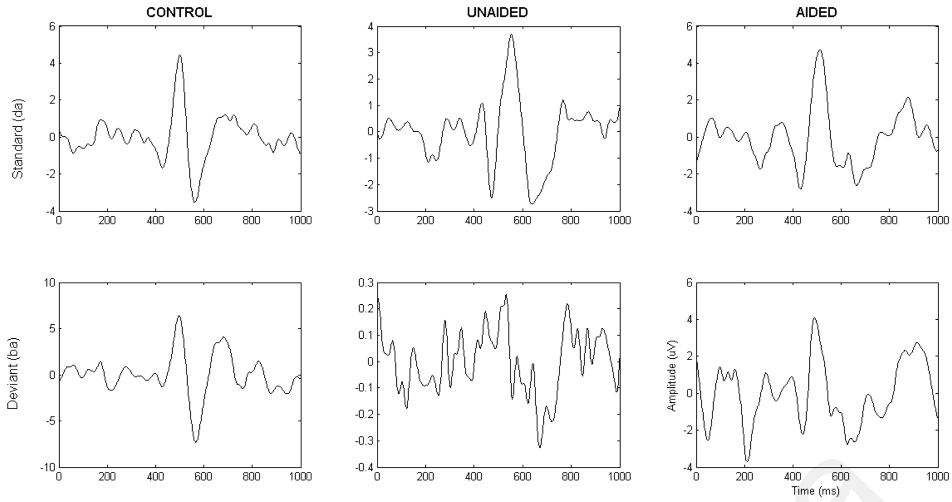

Figure 4.2: A sample CAEP from both standard and deviant stimuli for control subject and SNHL subject (Aided and Unaided) from Cz electrode, the marker is at 200 ms

As specified in the analysis section in Chapter 3, the correlation coefficient test and t-test were applied to the control subjects' data where the mean and the standard deviation for both amplitude and latencies for all subjects are shown in Table 4.1. The results of the correlation coefficient test showed high resemblance between this study results and CAEP waveforms that were outlines in previous studies. In addition, the p-value of the t-test also confirmed that there is only small difference.

The analysis of the amplitude of the CAEP's components for the control subjects both standard and deviant responses revealed that no main effects were statistically significant ($p < 0.2546$), where all components were larger in standard stimulus compared to deviant stimulus.

Table 4.1: Mean amplitudes in (μV) and latencies in (ms) with standard deviations for the recorded CAEP components of the 10 control subjects

	Amplitude (μV)									
	P1		**N1**		**P2**		**N2**		**P3**	
	da	**ba**	**da**	**ba**	**da**	**ba**	**da**	**ba**	**da**	**ba**
Mean	1.27	0.62	1.02	0.75	2.49	0.43	2.90	1.35	3.01	2.64
SD	0.42	0.34	0.38	0.45	0.95	0.22	0.61	0.35	0.76	0.67
	Latency (ms)									
	P1		**N1**		**P2**		**N2**		**P3**	
	da	**ba**	**da**	**ba**	**da**	**ba**	**da**	**ba**	**da**	**ba**
Mean	83	68	152	117	192	194	271	272	358	362
SD	39	30	41	29	32	36	25	26	16	24

The analysis of the latencies of the CAEP's components for the control subjects for both standard and deviant responses revealed a statistically significant ($p < 0.001$) of the main effects. Whereas, CAEP components (P2, N2 and P3) showed larger latencies to responses to deviant stimulus compared to responses to standard stimulus. The only exceptions were N1 and P1 waves, which showed opposite pattern.

The mean and standard deviation of the amplitudes (peak to peak) and latencies of the CAEP components (P1, N1, P2, N2, and P3) for SNHL group are shown in Table 4.2. They are compared with the control subjects' results in Figure 4.3, 4.4, 4.5 and 4.6. The table shows the results for both unaided and aided cases.

Table 4.2: Mean amplitudes in (µV) and latencies in (ms) with standard deviations for the recorded CAEP components of the 10 SNHL subjects

		Amplitude (µV)									
		P1		**N1**		**P2**		**N2**		**P3**	
		da	**ba**	**da**	**ba**	**da**	**ba**	**da**	**Ba**	**da**	**ba**
Unaided	**Mean**	0.54	1.11	0.99	2.27	0.30	1.25	0.83	1.42	2.63	5.18
	SD	0.88	0.84	0.96	3.01	0.16	1.06	1.02	1.49	1.72	3.9
Aided	**Mean**	1.66	3.07	1.98	4.13	1.59	2.21	1.24	3.14	3.94	7.79
	SD	2.92	4.25	3.88	5.66	2.20	2.16	0.8	3.60	5.5	6.54
		Latency (ms)									
		P1		**N1**		**P2**		**N2**		**P3**	
		da	**ba**	**da**	**ba**	**da**	**ba**	**da**	**Ba**	**da**	**ba**
Unaided	**Mean**	71.1	66.2	102	100	164.0	169.0	214.0	214.0	330.0	335.0
	SD	10.5	8.11	16.4	20.1	17.7	19.4	22.3	48.3	40.3	34.1
Aided	**Mean**	74.2	72.2	98	108	158.0	162.0	212.0	218.0	321.0	324.0
	SD	9.62	12.9	24	29	12.1	17	22	25	16	35

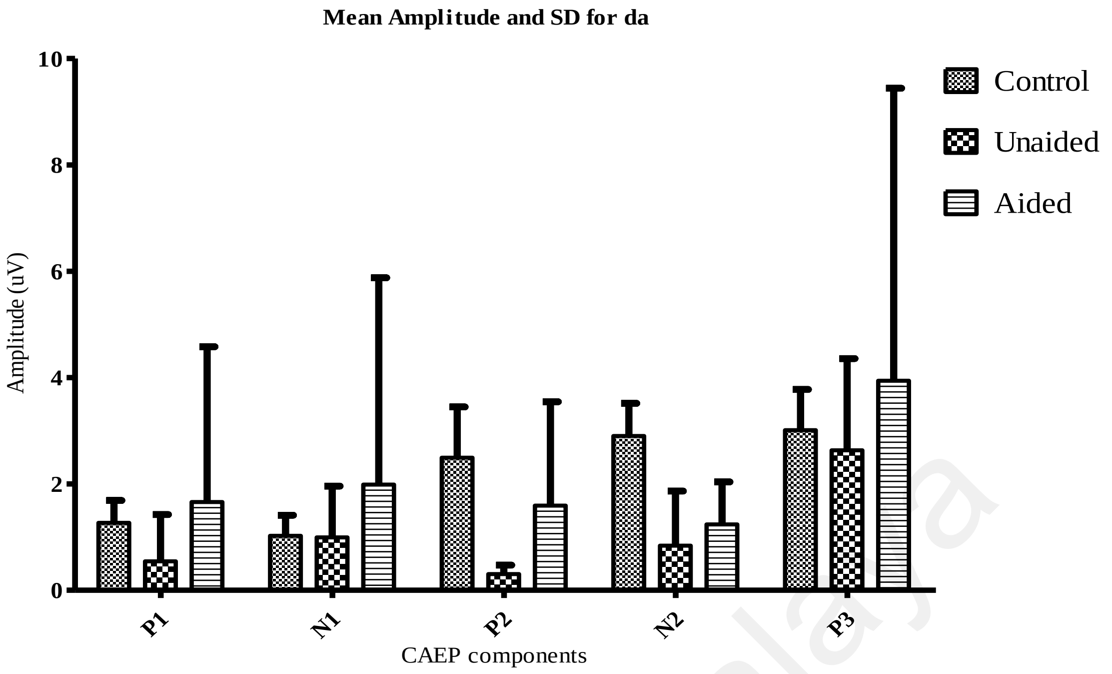

Figure 4.3: Mean amplitudes in (µV) with standard deviations for the recorded CAEP components of the SNHL subjects in response to Da stimulus

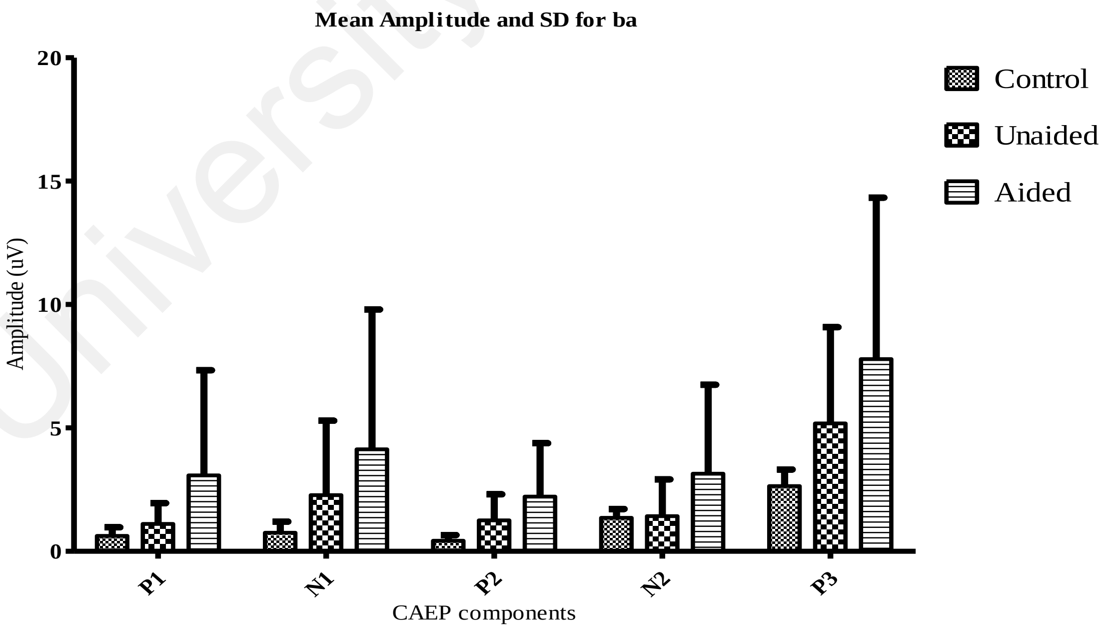

Figure 4.4: Mean amplitudes in (µV) with standard deviations for the recorded CAEP components of the SNHL subjects in response to ba stimulus

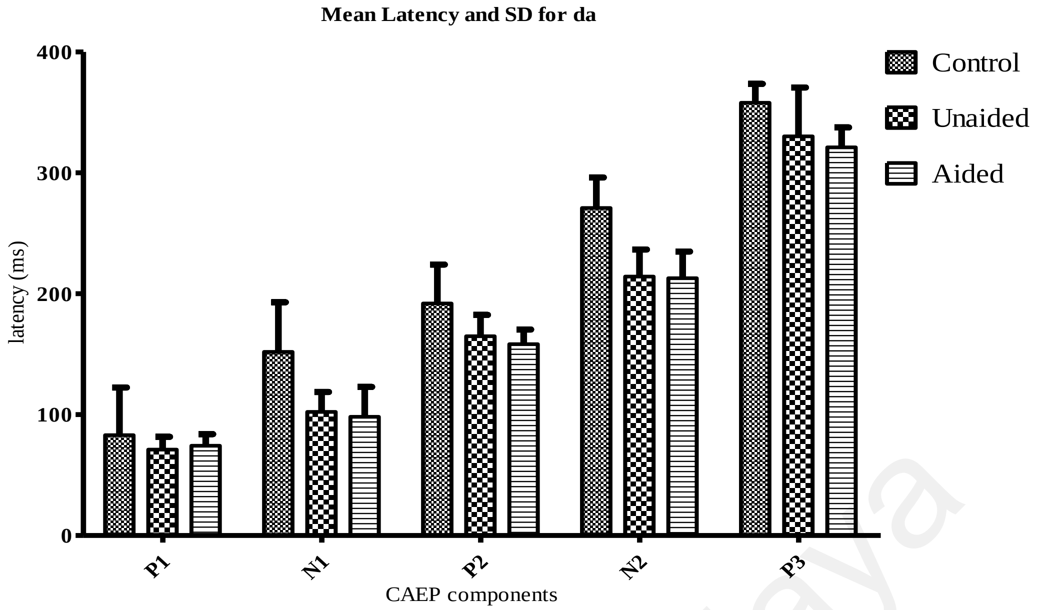

Figure 4.5: Mean Latency in (ms) with standard deviations for the recorded CAEP components of the SNHL subjects in response to da stimulus

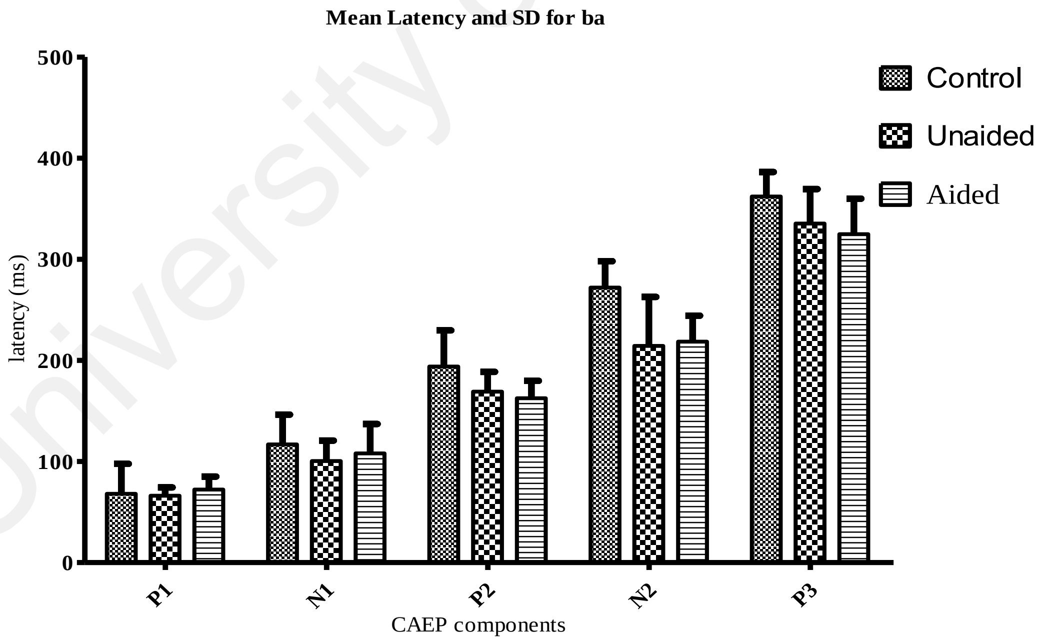

Figure 4.6: Mean Latency in (ms) with standard deviations for the recorded CAEP components of the SNHL subjects in response to ba stimulus

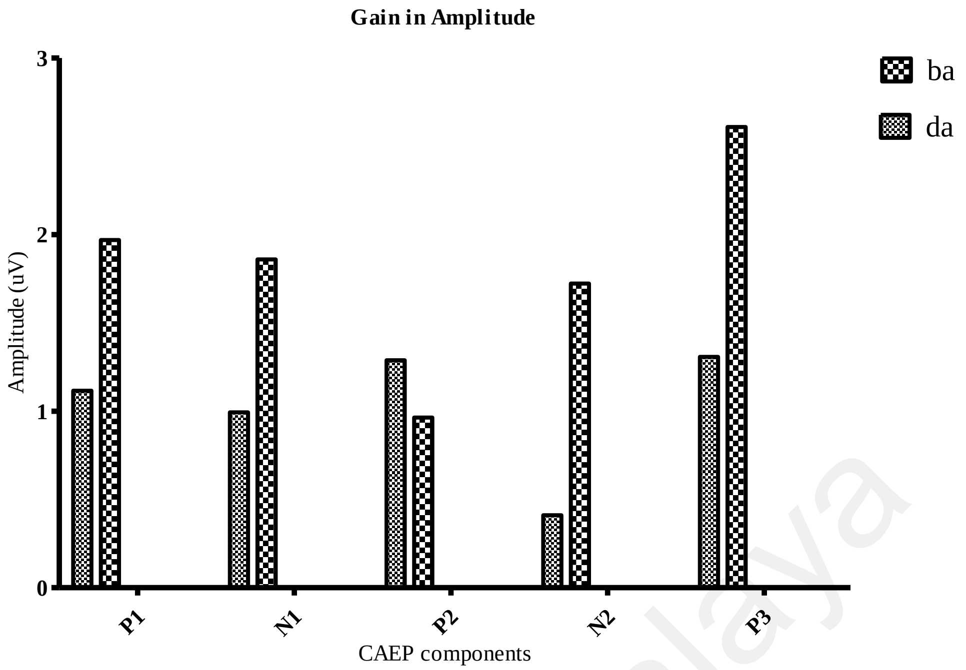

Figure 4.7: Gain in amplitude between the unaided and aided condition for both stimuli

The gained amplitude and latency between the unaided and aided condition for both stimuli were calculated to show how the hearing aids contributed to the CAEP components as shown in Figure 4.7 and 4.8 respectively.

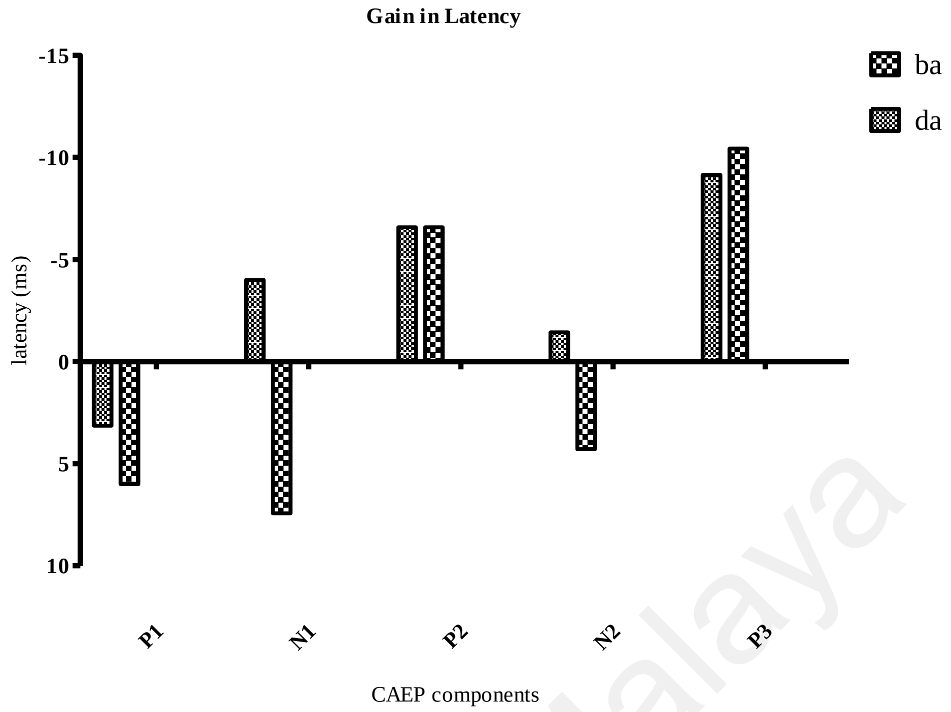

Figure 4.8: Gain in latency between the unaided and aided condition for both stimuli

4.3 Statistical Analysis

No significant differences were observed when one-way ANOVA was performed between averaged amplitudes and latencies of control, Unaided and aided data in response to the standard stimulus (da) where ($F = 1.988$, $p = 0.1796$) for the mean amplitude and ($F = 0.005$, $p = 0.9942$) for the mean latencies. The differences were only considered significant at a level of $p < 0.05$. The right side of Figure 4.9 shows a graph of the obtained results for the mean amplitude for da stimulus and the right side of Figure 4.10 shows a graph of the obtained results for the mean latencies for da stimulus.

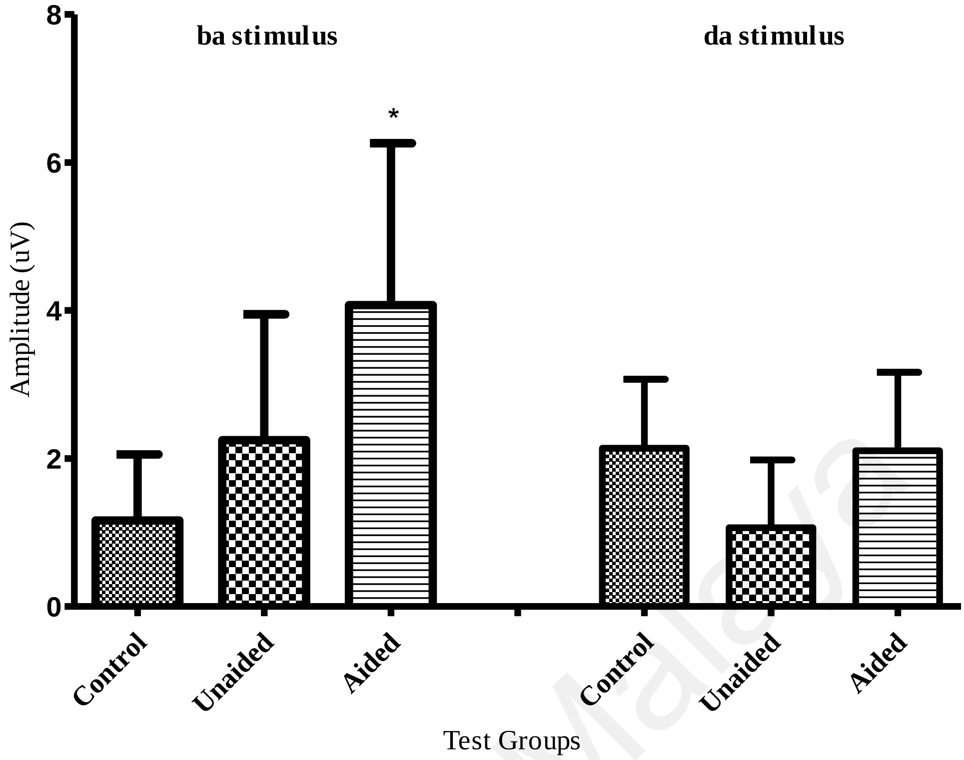

Figure 4.9: ANOVA test results for the mean amplitude between control, Unaided and aided data in response to both stimuli

One-way ANOVA test also showed no significant difference when it was performed between averaged amplitudes and latencies of control, Unaided and aided data in response to the deviant stimulus (ba) where (F =3.837, p =0.0515) for the mean amplitudes and (F =0.079, p =0.923) for the mean latencies. The differences were only considered significant at a level of $p < 0.05$. The left side of Figure 4.9 shows a graph of the obtained results for the mean amplitude for ba stimulus and the left side of Figure 4.10 shows a graph of the obtained results for the mean latencies for ba stimulus. However, with small difference between the test p-value and significant level p-value, 0.0515 and 0.05 respectively, Tukey's multiple comparison test was done to see if there is any significant difference between each pair of columns. The results showed only significant difference between the control and the aided group where the p-value was less than 0.05. This is indicated by a star over the aided column in Figure 4.9.

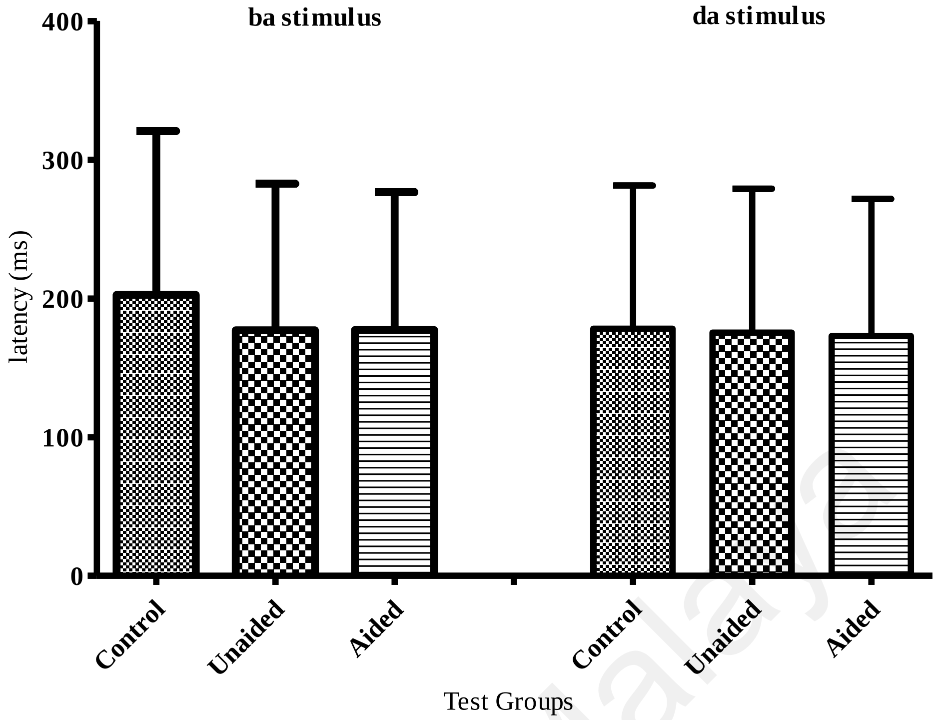

Figure 4.10: ANOVA test results for the mean latency between of control, Unaided and aided data in response to both stimuli

After comparing the means of the three groups to test if there are any significant differences between them, t-test was then performed between the mean amplitude of the responses to the standard and deviant stimuli during unaided and aided cases. The results indicated that the responses to ba and da differ significantly where p-value was 0.0006<0.05. The results are depicted in Figure 4.11. The test was repeated on the mean latency of the responses to the standard and deviant stimuli during unaided and aided cases. The results indicated that the responses to da and ba do not differ significantly where p-value was 0.48<0.05. The results are depicted in Figure 4.12.

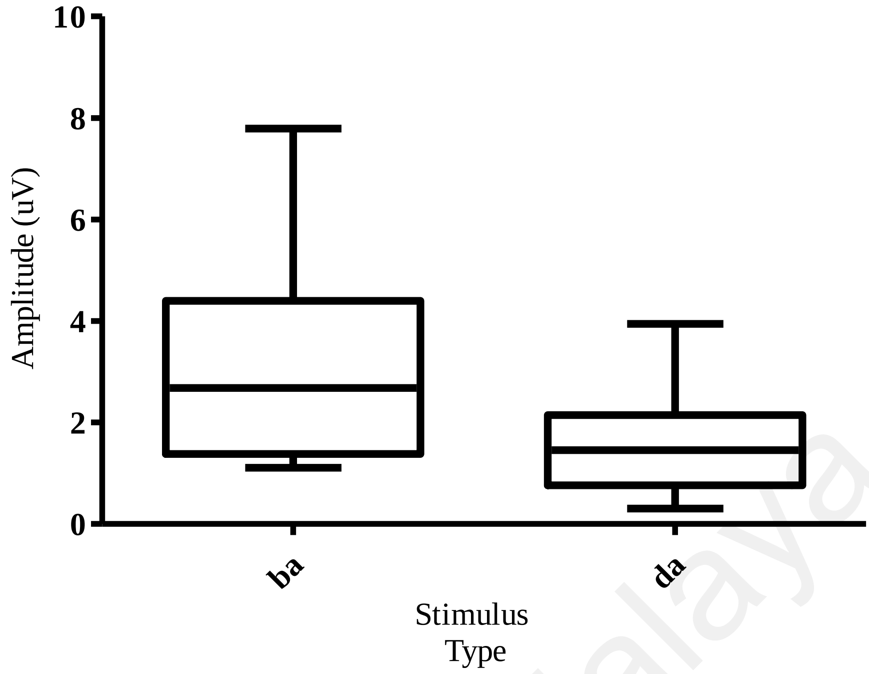

Figure 4.11: T-test results for the mean amplitude of the standard and deviant responses for unaided and aided conditions

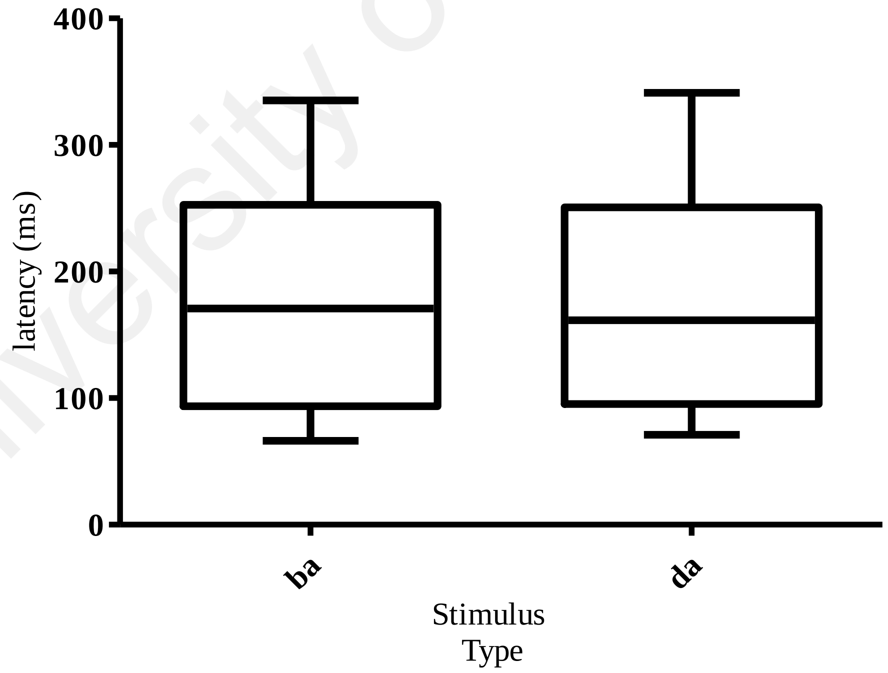

Figure 4.12: T-test results for the mean latency of the standard and deviant responses for unaided and aided conditions

CHAPTER 5: DISCUSSION

This discussion section is divided into sections which are as follows:

5.1 Summary of Main Findings

The present study examined the effects of CAEPs and hearing aids on speech perception on SNHL individuals. CAEPs recording were collected from 22 participants, 12 of them had normal hearing threshold and 10 of them suffered SNHL. The latencies and amplitudes were measured in response to the speech stimuli and then analyzed. Overall, the results for the Control subjects showed that the components N1, P1, P2, N2 and P3 of CAEP were clearly visible in response to both stimuli. The correlation coefficient test showed high resemblance between present study results and previous similar studies using English CV by native English speakers (Näätänen, 1992; Julia L Wunderlich & Cone-Wesson, 2001). On the other hand, the results from SNHL subjects showed clear CAEP components in the aided condition where the hearing aids improved the responses compared to unaided condition. As can be seen from Figure 4.7 and Figure 4.8, the results showed that hearing aid's usage had an increase to the amplitude and a decrease to the latency of most of this subject's CAEP components. These response changes are at both standard and deviant stimuli, where, for example, the latencies are approximately 30 ms shorter for P3 and the amplitudes of P3 are approximately 30% greater in the aided versus unaided condition. These results are in agreement with the previous studies where it is expected that hearing aids improve the CAEP responses (P. A. Korczak et al., 2005; Oates et al., 2002). This was confirmed by ANOVA results between the three groups (see in Figure 4.9 and 4.10) where there was a gain in amplitude and a decrease in latency in the aided conditions compared to the unaided condition despite the insignificant differences.

In light of the aforementioned findings, the main goal of this study was to find which components of CAEP gained the most benefit from the use of hearing aids in assessing the speech detection and discrimination in SNHL individuals. Figure 4.7 revealed that P3 gained the highest amplitude in both standard and deviant stimuli compared to the other CAEP components. The mean latency also showed that P3 had the highest decrease among the other components as evident from Table 4.2 and Figure 4.8. The higher amplitudes and lesser latencies of P3 indicated that P3 had a better performance and had the most obvious effect by both stimuli in the aided condition. P3 results suggest that physiological evidences of the CV stimuli reached the auditory cortex and the individual heard the stimuli. According to a review by Stapells, the absence or presence of later CAEP components (e.g., N2 or P3) can provide clinicians with valuable information concerning the ability of the brain to detect and discriminate speech stimuli (Stapells, 2002). Figure 4.7 and 4.8 also demonstrated that P2 component followed the general pattern that hearing aids individuals acquire, where it gained higher amplitudes and lesser latencies between the aided and unaided conditions in both stimuli compared to the remaining components. The improvements or changes occurred to the P3 and P2 waves in both SNHL conditions, respectively, provide evidences that the speech sounds or signals have reached to the auditory cortex in a faster and more effective way and is therefore audible to the person wearing the hearing aids (Brett A Martin, Alain Sigal, Diane Kurtzberg, & David R Stapells, 1997; Näätänen & Picton, 1987). Owing to these results, P3 and P2 could be used in both clinical and research applications as a predictor and objective indicator of hearing aids performance in speech perception. The other components (P1, N1 and N2) showed a somewhat different pattern in their latencies responses where there was no reduction at all in P1 wave in both stimuli, and only very small reduction of both N1 and N2 waves in the standard stimulus (see Figure 4.8 for the gain in latency between aided and unaided conditions for SNHL subjects).

5.2 Differences in Amplitudes and Latencies with Stimulus Type

CAEP could provide information regarding the ability of the brain to differentiate between speech sounds or stimuli (e.g., /ba/ and /da/) and whether or not these differences reflect various levels of auditory processing. The current results showed that SNHL has different effects on various levels of auditory processing. This is evident in Figure 4.11 where t-test was performed between the two stimuli for the amplitude of all components and showed significant differences between the two stimuli as p-value was $0.0006<0.05$. However, t-test showed no significant differences between the latencies of both stimuli as evident in Figure 4.12. Furthermore, Table 4.2 shows that the differences between /da/ vs /ba/ stimuli in the later CAEP (e.g., P3) are higher than those in the early cognitive components (e.g., P2) where, for example, the mean amplitude increased nearly two times for P3 (i.e., from 3.94 µV to 7.79 µV) vs P2 (i.e., from 1.59 µV to 2.21 µV) in the aided condition. The difference was also evident in the latencies of both stimuli, however with only small one. These findings imply that as cognitive processes of the brain move from detection to discrimination of the speech signals, the difference between the two speech stimuli increases. Thus, this finding suggests that changes in the amplitudes and latencies of CAEP due to SNHL and hearing aids usage reflect various levels of auditory processing.

5.3 Comparison between Control and Aided SNHL Results

The capability of the brain to process the speech stimuli in normal hearing individuals versus SNHL individuals wearing hearing aids showed inconsistent results. One-way ANOVA test among the amplitudes of the three groups (control, unaided and aided) for the standard stimulus (da) shows no significant results where the p-value was

0.1792>0.05 (see the right side of Figure 4.9). This suggests that the brain processes the standard stimulus in a similar pattern for both the normal subjects and the aided SNHL subjects. The results of ANOVA for mean latency of the standard stimulus (da) also support this claim where there was only a small difference between the normal subjects and the aided SNHL subjects' results (see the right side of Figure 4.10). However, ANOVA results for the deviant stimulus (ba), interestingly, show a very small difference between p-values of 0.0515, which urged to do Tukey's post hoc test to determine if there is any significant difference between each pair of columns. The results showed that control group versus aided group differ significantly where the p-value was less than 0.05 (see the left side of Figure 4.9). This result suggests that the brain processes the deviant stimulus in a different pattern for both the normal subjects and the aided SNHL subjects despite the fact that there was no significant difference between the mean latencies. One possible explanation for why these results were found could be that hearing aid technology is still unable to handle all sounds and improvements are needed to get optimal satisfaction from wearers.

5.4 Advantages, limitations and further work of this study

An advantage of this research is that it was the first study to be done on Malay subjects using Malay voice. This opened a door for other researchers in Malaysia to further work or carry on similar studies taking in mind the outcomes of this research.

Although this study has reached its main goal, there were two unavoidable limitations. First of all, due to the unavailability of SNHL subjects and the limit of time, this study was conducted on a relatively small sample size. Therefore, to generalize the output for larger group, the research should have engaged more subjects. Second, this study is still only a theory and it hence needs an application to prove its results.

As there were drawbacks in this study, it is recommended that further work should be carried out to overcome these draws. First of all, to generalize the output for larger group, further attempts should be done to repeat the current work with a bigger SNHL sample size. This could be done by including lower degrees of hearing loss (e.g. between 40 to 55 dB) to the targeted population. Secondly, further work is also needed to extend the scope of this study. This could be done by developing a CAEP device which can be used to test the intensity of hearing loss taking in mind these findings.

On the other hand, as the study raised a concern that hearing aids technology still doesn’t provide optimal satisfaction for users. Further work therefore is suggested to find out the percentage of satisfaction hearing aids users get from their devices and what could be done to improve their functions so that they provide full satisfaction for users.

CHAPTER 6: CONCLUSION

The present study attempted to determine which CAEP components among (P1, N1, P2, N2, or P3) are most beneficial in assessing the abilities of adult SNHL population to detect and discriminate speech sounds. CAEPs were recorded from 12 adult Malay male subjects having normal hearing and 10 adults with SNHL while listening to Malaya consonant-vowel speech stimuli of /ba/ and /da/. The results showed that the P3 and P2 components followed the general pattern that hearing aids individuals acquire, where they gained higher amplitudes and lesser latencies between the aided and unaided conditions in both stimuli compared to the remaining components. This indicates that P3 and P2 components had a better performance and had the most obvious effect by both stimuli in the aided condition compared to the unaided condition. Therefore, this study suggests that P2 was the most beneficial components in assessing the speech detection ability and P3 was the most beneficial component in assessing the speech discrimination abilities of the adult SNHL population in Malaya subjects.

The study also attempted to find whether changes in the amplitudes and latencies of these CAEP components occurring with Sensorineural Hearing Loss (SNHL) and hearing aids reflect different stages of auditory processing. The results showed that SNHL has different effects on various levels of auditory processing.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

Journal publication

Mohammed G. Al-zidi, Jayasree Santhosh, Siew-Cheok Ng, Abdul Rauf A Bakar, Ibrahim Amer Ibrahim. “P2 and P3 as indicators of hearing aids performance in speech perception”. Journal of engineering research (ISI-Cited Publication). Accepted for publication.

Hua Nong Ting, Abdul Rauf A Bakar, Jayasree Santhosh, **Mohammed G. Al-Zidi**, Ibrahim Amer Ibrahim & Ng Siew Cheok. “Effects of Speech Phonological Features during Passive Perception on Cortical Auditory Evoked Potential in Sensorineural Hearing Loss”. Sains Malaysiana (ISI-Cited Publication). Accepted for publication.

Proceeding publication

Al-Zidi, M., Santhosh, J., & Rajabi, J. (2015). Alpha Rhythm Dominance in Human Emotional Attention States: An Experimentation with ‘Idling’ and ‘Binding’ Rhythms. In F. Ortuño & I. Rojas (Eds.), Bioinformatics and Biomedical Engineering (Vol. 9043, pp. 282-291): Springer International Publishing.