THE EFFICACY OF A COMPUTER ASSISTED AUDITORY TRAINING ON THE PLASTICITY OF THE CENTRAL AUDITORY NERVOUS SYSTEM IN HEARING IMPAIRED CHILDREN

by

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LIST OF ABREVIATIONS

ABR	auditory brainstem response
AERPs	auditory event related potentials
ALDs	assistive listening devices
ALR	auditory late response
AMLR	auditory middle latency response
ANCOVA	one-way analysis of covariance
APDs	auditory processing disorders
ASHA	American Speech and Hearing Association
ASSR	auditory steady state response
AVT	auditory verbal therapy
BEAM	brain electrical activity mapping
CAP	central auditory process
CAT	computerized auditory training
CANS	central auditory nervous system
CI	cochlear Implant
CV	consonant-vowel
CVI	content validity index
cABR	complex auditory brainstem response
DPOAE	distortion product otoacoustic emissions
dB	decibel
EDHI	early hearing detection and intervention
EEG	electroencephalography
ENT	Ear, Nose and Throat
ERPs	event related potentials
FFR	frequency following response
HAT	hearing assistance technology
HL	hearing level
HUSM	Hospital Universiti Sains Malaysia
I-CVI	item-level content validity index
LD	learning disability
MAIS	Meaningful Auditory Integration Scale
MCL	most comfortable level
MMN	mismatch negativity
MUSS	Meaningful Use of Speech Scale
myPRAT	Malay version of Parental Report on Auditory Training
ms	millisecond
NAT	novel auditory training

nHL	normal hearing level
OAE	otoacoustic emissions
OFC	occipital-frontal circumference
ORL	otorhinolaryngology
PTA	pure tone audiometry
RAT	regular auditory training
RCT	randomized control trial
sABR	speech auditory brainstem response
S-CVI	scale-level content validity index
SDS	speech discrimination score
SL	sensation level
SLI	specific language impairment
SPL	sound pressure level
SRT	speech reception threshold
SFOAE	stimulus frequency otoacoustic emissions
TEOAE	transient evoked otoacoustic emissions
UK	United Kingdom
USA	United State of America
USM	Universiti Sains Malaysia
V/A	complex of waves V and A of sABR
Ω	Ohm
KΩ	Kilo Ohm
μV	microvolt
Hz	Hertz

KEBERKESANAN LATIHAN AUDITORI BERKOMPUTER PADA NEUROPLASTISITI SISTEM SARAF AUDITORI PUSAT DALAM KALANGAN KANAK-KANAK BERMASALAH PENDENGARAN

ABSTRAK

Untuk meningkatkan kemahiran mendengar dan bertutur, kanak-kanak bermasalah pendengaran jenis sensorineural perlu menggunakan alat bantu pendengaran dan menjalani program pemulihan pendengaran tertentu termasuk latihan auditori. Latihan auditori berkomputer *(CAT)* telah terbukti berkesan dalam meningkatkan kemahiran mendengar dan sesuai untuk kanak-kanak. Versi Melayu *CAT*, bagaimanapun, belum didapati untuk tujuan klinikal. Tujuan utama kajian ini adalah untuk menentukan keberkesanan latihan auditori berkomputer baru *(NAT)* (berbanding latihan auditori biasa, *RAT*) dengan merekodkan *speech-evoked auditory brainstem response* (*sABR*) pada dua kumpulan kanak-kanak bermasalah pendengaran sebelum dan selepas menjalani intervensi.

Setelah selesai melakukan kajian awal, keberkesanan *NAT* dalam mempercepatkan proses neuroplastisiti diuji. Kanak-kanak normal (n=17, min umur = 5.6 ± 1.6 tahun), kanak-kanak bermasalah pendengaran yang menjalani program *NAT* (n=9, min umur = 7.00 ± 2.06 tahun) dan kanak-kanak bermasalah pendengaran yang menjalani program *RAT* (n=11, min umur = 7.72 ± 1.48 tahun) menyertai kajian ini. Untuk sesi pra-intervensi, ibu bapa kanak-kanak bermasalah pendengaran (dalam kedua-dua kumpulan *NAT* dan *RAT*) perlu mengisi borang soal selidik *Meaningful Auditory Integration Scale (MAIS)*. Ketiga-tiga kumpulan kanak-kanak tersebut kemudian menjalani ujian *sAB.* Empat bulan selepas intervensi, *MAIS*, *myPRAT* dan *sABR* direkodkan daripada kumpulan kanak-kanak bermasalah pendengaran. Kanak-kanak normal hanya dikehendaki menjalani ujian *sABR.*

Untuk analisis jantina, walau pun terdapat perbezaan signifikan dalam keputusan *sABR* antara lelaki dewasa dan wanita, didapati tiada perbezaan signifikan dalam kalangan kanak-kanak. Dalam kajian utama, berdasarkan analisis *MAIS* dan *myPRAT*, kedua-dua kaedah *NAT* dan *RAT* didapati berkesan dalam meningkatkan kemahiran mendengar ($p<0.05$). Walau bagaimanapun, kaedah *NAT* didapati lebih baik daripada program *RAT* seperti yang ditunjukkan oleh saiz kesan yang lebih besar. Dalam ujian *sABR*, kesan kehilangan pendengaran dapat dilihat dengan jelas apabila ketiga-tiga kumpulan dibandingkan, terutamanya bagi puncak *V* dan *A* ($p<0.05$). Berdasarkan analisis antara kumpulan, masa min untuk puncak *C* menjadi lebih baik selepas intervensi dalam kumpulan *NAT*.Untuk perbandingan secara *intra*,amplitud min yang lebih tinggi diperhatikan untuk puncak V dalam kumpulan *NAT* selepas intervensi (seperti yang ditunjukkan oleh saiz kesan sederhana). Corak sebegini tidak dilihat dalam kumpulan *RAT*. Selepas intervensi, perbezaan signifikan masih didapati pada *V/A slopes* antara kumpulan normal dan *RAT*, tetapi tiada perbezaan ketara dilihat antara kumpulan normal dan *NAT* untuk kesemua keputusan *sABR composite onset measures*. Sebab yang mungkin untuk penemuan ini dibincangkan.

Kelebihan kaedah *NAT* dalam mempercepatkan proses neuroplastisiti mungkin disebabkan oleh kandungannya dan penekanan kepada aspek masa dalam program ini. Kajian ini menawarkan beberapa faedah kepada masyarakat, universiti dan peningkatan pengetahuan. Versi Melayu *NAT* yang baru dibangunkan boleh digunakan oleh ahli klinikal sebagai kaedah pemulihan alternatif untuk meningkatkan kemahiran mendengar kanak-kanak bermasalah pendengaran.

THE EFFICACY OF A COMPUTER ASSISTED AUDITORY TRAINING ON THE PLASTICITY OF THE CENTRAL AUDITORY NERVOUS SYSTEM IN HEARING IMPAIRED CHILDREN

ABSTRACT

For improving auditory and speech skills, children with sensorineural hearing loss are required to use hearing amplifications devices and undergo a specific auditory rehabilitation program including auditory training. Computerized auditory training (CAT) has been shown to be effective in improving listening skills and enjoying for children. The Malay version of CAT, nevertheless, was not available for clinical applications. The main aim of the present study was to determine the effectiveness of a Newly-computerized Auditory Training (NAT) (when compared with regular auditory training, RAT) by recording speech-evoked auditory brainstem response (sABR) peaks in two groups of hearing impaired children before and after undergoing intervention.

After completing the preliminary studies, the effectiveness of NAT in promoting neuroplasticity was tested. Eligible normal children (n=17, mean age = 5.6 ± 1.6 years), hearing impaired children who underwent NAT program (n=9, mean age = 7.00 ± 2.06 years) and hearing children who underwent regular auditory training (RAT) (n=11, mean age = 7.72 ± 1.48 years) were recruited. For pre-intervention session, parents of hearing impaired children (in both NAT and RAT groups) were instructed to fill in Meaningful Auditory Integration Scale (MAIS) questionnaire. All three groups of children then underwent sABR testing. Four months after the intervention, MAIS, myPRAT and sABR were recorded from the hearing impaired groups and the normal children were only required to undergo sABR testing.

For the gender analyses, while significant differences in sABR results were found between men and women, no such effect was seen in children. In the main study, based on MAIS and myPRAT analyses, both NAT and RAT methods were found to be effective in improving auditory skills ($p<0.05$). However, the NAT method was found to be superior to RAT as indicated by stronger effect sizes. In sABR testing, the effect of hearing loss was clearly noted when the three groups were compared, particularly for peaks V and A ($p<0.05$). Based on the inter-group analysis, the mean latency of peak C improved after the intervention in the NAT group. For intra-group comparison of sABR, higher mean amplitude of peak V was observed in the NAT group after the intervention (as shown by the moderate effect sizes). No such pattern was seen in the RAT group. After the intervention, while significant differences in V/A slopes were found between normal and RAT groups, no notable differences were found between normal and NAT groups for all sABR composite onset measures. The possible reasons for these findings are discussed accordingly.

The superiority of NAT method in promoting neuroplasticity is perhaps due to its materials and emphasis on the temporal aspect in the program. The present study offers several benefits to community, university and knowledge enhancement. The newly developed Malay version of NAT is now available to be used by clinicians as an alternative rehabilitative method for improving the listening skills of hearing impaired children.

CHAPTER 1

BACKGROUND OF STUDY

1.1.Introduction

Hearing loss is common among children. Figure 1.1 shows the prevalence of disabling hearing loss in children (< 14 years old) worldwide according to WHO report. According to the international scientific report entitled "Evaluation of the Social and Economic Costs of Hearing Impairment" by Shield (2006), in Europe, the untreated hearing loss costs 213 billion Euros per year. Figures of a similar order of magnitude have been estimated in the USA (Ruben, 2000) and Australia (Anon, 2006).

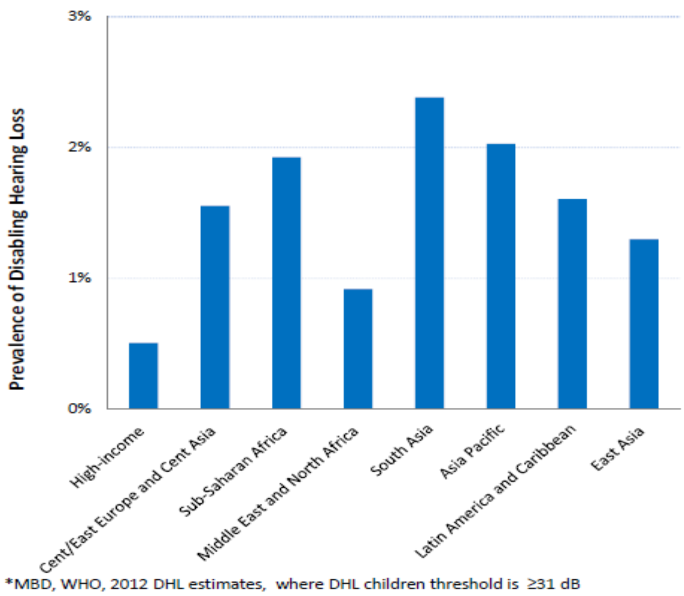

Figure 1.1. Prevalence of disabling hearing loss in children 0 – 14 years in different parts of the world in 2012. (Source: Report of WHO, Hearing Loss estimates)

To limit negative consequences of hearing loss, early hearing detection and intervention (EDHI) must be implemented. The undetected hearing loss can cause a delay or retardation in speech and language in children and adults. EDHI has two important impacts on the life of children with hearing impairment. Firstly, its effecton the development of language and secondly, effect on the related costs (e.g. hearing aids purchase, special education services etc.). In other words, it causes a deficit in communicational skills of children and adults and imposes additional expenses to the society.

There are four types of Hearing loss including conductive, sensorineural, mixed hearing loss and central deafness. On the other side, there are three options for treatment hearing loss as follows:

a) Medication

b) Surgical Treatment

- Reconstructive surgery
- Middle ear implant
- Cochlear implant (CI)
- Brainstem implant

c) Habilitation and Rehabilitation

- Hearing aids
- Assistive listening devices (ALDs)
- Large Area Listening Systems
- Television Listening Systems
- Conference Microphones
- Personal FM Systems
- Amplified Telephones
- Auditory Training

While the conductive hearing losses are mostly treatable medically and surgically, the sensorineural hearing loss is permanent and the use of hearing assistance technology (HAT) such as hearing aids or cochlear implants is required for improving hearing.

After being fitted with the appropriate amplification devices, the children need to undergo auditory training for improving their auditory and speech skills. While some aspects of auditory training can be performed by audiologists, speech language pathologists are the main professionals who provide an intensive speech therapy program for hearing impaired children.

Following the specific auditory training program, improvements in hearing and speech skills should be noted. In this regard, neural (or brain) plasticity is said to occur. The neural plasticity is defined as the ability of the nervous system to respond to intrinsic or extrinsic stimuli by reorganizing its structure, function and connections (Cramer et al., 2011). Even though the brain plasticity is more prominent in the early childhood (Pascual-Leone et al., 2005), it may also occur even into adulthood (Rakic, 2002). In the field of auditory physiology, cortical auditory evoked responses are typically carried out for documenting the neural plasticity. The auditory late response (ALR) and event related potential (ERP) are examples of common auditory evoked responses to determine brain plasticity among subjects after undergoing specific auditory training programs (Benasich et al., 2015; Tamminen et al., 2015).

1.2. Problem statement

As mentioned earlier, it is clear that appropriate and timely action in detecting hearing loss is very important. After the hearing loss detection, early intervention must be carried out as as soon as possible to make full use of neural plasticity, so that greater improvements can be seen in auditory and speech abilities.

Depending on many factors, the progress after auditory rehabilitation can vary. Apart from the early detection and early intervention issue, type of auditory training is also important. In this regard, many studies have shown that the computerized auditory training (CAT) is more effective than the regular auditory training in improving auditory skills (Loo et al., 2016), language (Szelag et al., 2015), memory (Mawjee et al., 2015), attention (Shin et al., 2016) and so on. Furthermore, the CAT method is more systematic and enjoying for children (Loo et al., 2010). On the other side, we can consider that CAT also has some limitations. Actually, CAT as a based computerized auditory training is very dependent to computer and this dependency sometimes and in some places like rural areas cause to not using of it, because every person cannot access to a computer in such places.

Furthermore, according to Flexer (1990), audiologists should be more active in providing audiological rehabilitation services including auditory training. Since the progress of therapy is influenced by many factors including the setting of amplification devices, it seems logical for audiologists to perform the auditory training. For example, if a hearing impaired child is not able to detect certain phonemes, the audiologist can readjust the setting of the hearing aids immediately. Consequently, the auditory training can be performed with the most optimum setting of amplification devices and perhaps good outcomes will be obtained. Speech language pathologists, on the other hand, are not trained to fine tune the setting of hearing aids but they are the main professionals that provide auditory rehabilitation for hearing impaired patients. In this regard, audiologists should play more roles in the field of auditory rehabilitation and perhaps by having CAT program, more audiologists will get involved.

On the other side, having advanced methods for treatment of hearing impairments and also using advanced methods for auditory rehabilitation alone are not enough to treat hearing loss. The important thing is that we should be able to measure the auditory skills of the people with hearing loss especially in children. Thus having a safe and confident tool for measuring the improvent of auditory skills of hearing impaired people is very necessary. During the past two decades, speech auditory brainstem response (sABR) has been shown a good competency in representing the changes in the central auditory nervous system (CANS).

Auditory brainstem response (ABR) represents electrophysiological activities from the auditory brainstem. It has been used in many clinical applications including objective hearing threshold determination (Mishra et al., 2013; Maloff and Hood, 2014), site of lesion testing (Peterein and Neely, 2013), intra-operative monitoring (Kim et al., 2013), diagnosis of acoustic neuroma (Koors et al., 2013) and so on. More recently, ABRs evoked by speech stimuli have been reported and the outcomes are promising (Skoe et al., 2014). Contrary to the conventional click-evoked ABR, speech-evoked ABR (sABR) is recorded by presenting speech syllable such as /da/ repetitively (Hornickle et al., 2009). The sABRhas been used for detecting the improvements of auditory skills in many studies (Filippini et al., 2012; Krishnamurti et al., 2013; Skoe and Kraus, 2013; Strait et al., 2013). However, till date, no study that utilizes sABR to document neural plasticity in hearing impaired children has been performed.

By considering the aforementioned issues, there is a need to have a computerized auditory training program that is suitable for Malay children. This program would be designed in such as way that it would be effective in improving auditory skills. The present study, therefore, was carried out to develop a newly-computerized auditory training (NAT) and determine its efficacy in intervening hearing impaired children. The performance of NAT would also be compared with the regular auditory training (RAT) that is provided in the Speech Pathology Clinic, Hospital Universiti Sains Malaysia. To compare the effectiveness of these training programs, subjective and objective assessments were carried out. For subjective documentation, Meaningful Auditory Integration Scale (MAIS) and a new questionnaire (Malay version of Parental Report on Auditory Training, myPRAT) were used. For objective documentation, sABR assessment was used.

1.3. Aims and objectives of the study

1.3.1. General objectives

To determine the efficacy of a Newly-computerized Auditory Training (NAT) in improving auditory skills of Malay hearing impaired children.

1.3.2. Specific objectives

1.3.2.1. To determine the optimum protocol to record sABR among hearing impaired subjects.

1.3.2.2. To study the gender influence on sABR in healthy Malay adults and children.

1.3.2.3. To develop and validate a Malay version of Parental Report on Auditory Training (myPRAT) questionnaire for documenting the progress of auditory training subjectively.

1.3.2.3. To develop and validate the Newly-computerized Auditory Training (NAT) as a new intervention procedure

1.3.2.4. To compare NAT and RAT groups for pre- and post-intervention sessions by comparing the scores ofMAIS and myPRAT (inter-group comparison)

1.3.2.5. To compare the results of pre- and post-intervention sessions in each groupby using the scores of MAIS (intra-group comparison)

1.3.2.6. To compare the results of sABR between normal, NAT and RAT groups for pre- and post-intervention sessions by comparing the latencies and amplitudes (inter-group comparison)

1.3.2.7. To compare the results of sABR between pre- and post-intervention sessions in each groupby comparing the latencies and amplitudes of the peaks(intra-group comparison)

1.3.3. Research questions

Based on the objectives, the present study aimed to answer the following research questions:

1.3.3.1. Is there any significant difference between sexes in sABR results in healthy adults?

1.3.3.2. Is there any significant difference between sexes in sABR results in healthy children?

1.3.3.3. Is there any significant difference in MAIS results between NAT and RAT groups for pre- and post-intervention sessions? (Inter-group comparison)

1.3.3.4. Is there any significant difference in MAIS results between pre- and post-intervention sessions? (Intra-group comparison)

1.3.3.5. Is there any significant difference in myPRAT results between NAT and RAT groups for pre- and post-intervention sessions? (Inter-group comparison)

1.3.3.6. Is there any significant difference in latencies of sABR peaks among normal, NAT and RAT groups for pre- and post-intervention sessions (inter-group comparison)?

1.3.3.7. Is there any significant difference in latencies of sABR peaks between pre- and post-intervention sessions for each group (intra-group comparison)?

1.3.3.8. Is there any significant difference in amplitude of sABR peaks among normal, NAT and RAT groups for pre- and post-intervention sessions? (Inter-group comparison)

1.3.3.9. Is there any significant difference in amplitude of sABR peaks between pre- and post-intervention sessions for each group? (Intra-group comparison)

1.3.4. Hypothesis of the study

1.3.4.1. Null hypothesis: there is no significant difference in sABR results between sexes in healthy adults.

1.3.4.2. Null hypothesis: there is no significant difference in sABR results between sexes in healthy children.

1.3.4.3. Null hypothesis: there is no significant difference in MAIS results between NAT and RAT groups for pre- and post-intervention sessions.

1.3.4.4. Null hypothesis: there is no significant difference in MAIS results between pre- and post-intervention sessions in each group.

1.3.4.5. Null hypothesis: there is no significant difference in myPRAT results between NAT and RAT groups for post-intervention session.

1.3.4.6. Null hypothesis: there is no significant difference in latencies of sABR peaks between normal, NAT and RAT groups for pre- and post-intervention sessions.

1.3.4.7. Null hypothesis: there is no significant difference in latencies of sABR peaks between pre- and post-intervention sessions in each group.

1.3.4.8. Null hypothesis: there is no significant difference in amplitudes sABR peaks between normal, NAT and RAT groups for pre- and post-intervention sessions.

1.3.4.9. Null hypothesis: there is no significant difference in amplitudes of sABR peaks between pre- and post-intervention sessions in each group.

1.4. Research Design

In order to answer all the research objectives, this study was carried out in four consecutive stages described in the specific chapters of the thesis. Figure 1.2 illustrates the stages involved in the study. As depicted, in Stage 1, a descriptive preliminary study was performed to determine the optimum protocols to record sABR in a group of adults and children. In Stage 2, the second preliminary validation study was conducted to develop and validate the Malay version of Parental Report on Auditory Training (myPRAT). In Stage 3, the third preliminary validation study was performed to develop and validate the Newly-computerized Auditory Training (NAT) to be used in the main study. The main study was carried out in the final stage (Stage 4). Utilizing randomized control trial (RCT) design with single blind, in this stage, the effectiveness of NAT (compared to RAT) was determined among hearing impaired children. Chapter 3 of the thesis reveals the methodology for this main study, while the results are shown in Chapter 4. Relevant discussions are provided in Chapter 5 and the conclusion of this study is shown in Chapter 6.

1.5. The importance of study

The necessity and importance of the present study can be seen from different aspects. As an effort to provide better services to hearing impaired children, the present study developed the computerized auditory training that is suitable for Malay children. To the best of our knowledge, no validated computerized auditory training (that is culturally appropriate) has been developed for Malay children. The commercially available training programs are mostly in English version and may not be suitable for Malay children. In addition, the present study is the first to record sABR among Malay adults and children. Apart from providing novel information regarding the potential use of sABR in documenting neural plasticity in hearing impaired children, several pilot studies were also performed to verify the influence of demographic factor on sABR (e.g. gender). Normative data for Malay adults and children were also produced as guidelines for subsequent studies of sABR.

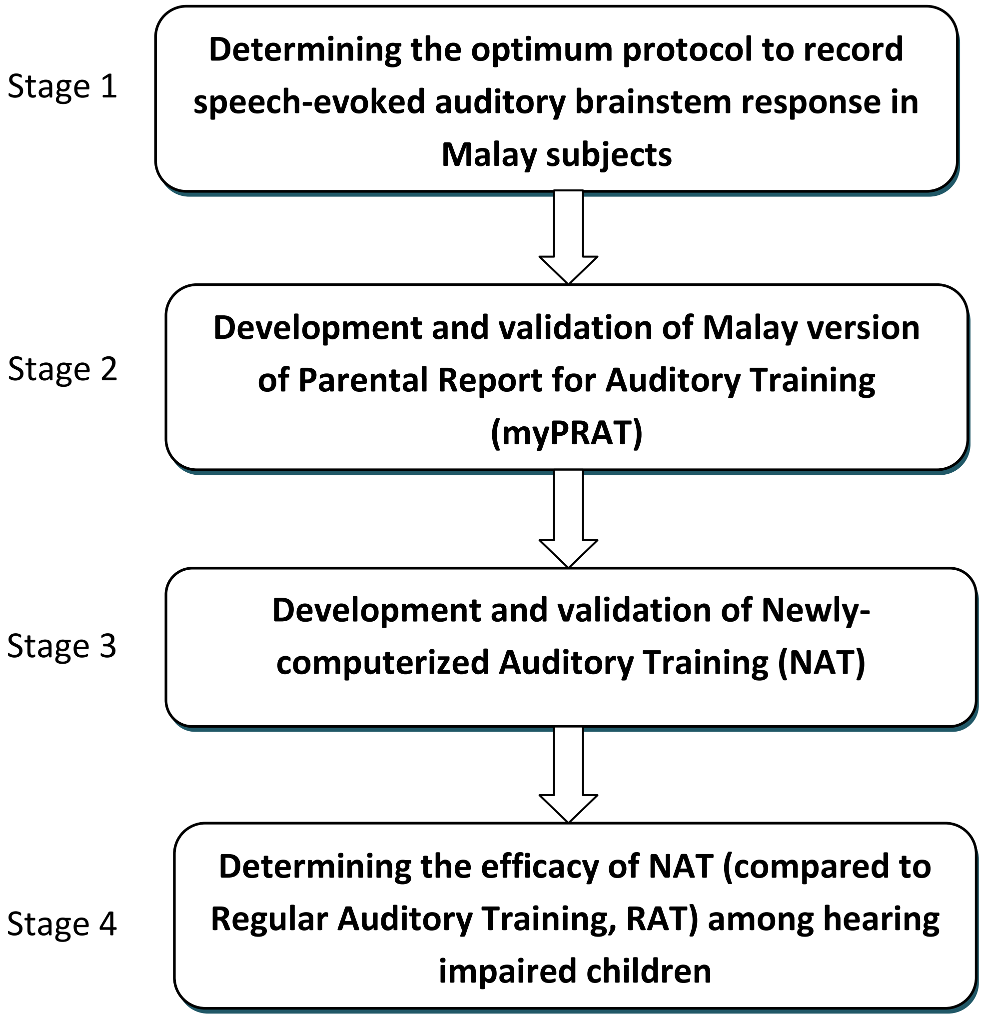

Figure 1.2. The flowchart showing the stages of the present study.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of anatomy and physiology of the auditory system

Hearing system in human comprises of four parts: External ear, middle ear, inner ear and auditory nerve along with CANS. The outer and middle ears convey sound vibrations toward inner ear and so are called the conductive parts of hearing system. The middle ear has an important role to matching the impedance between the air and fluids in the inner ear. Theinner ear is the sensory part of this system which converts mechanical vibrations to electrical energy. This type of energy is transferable through the auditory nerve and CANS. All the parts of hearing system are shown in Figures 2.1 and 2.2.

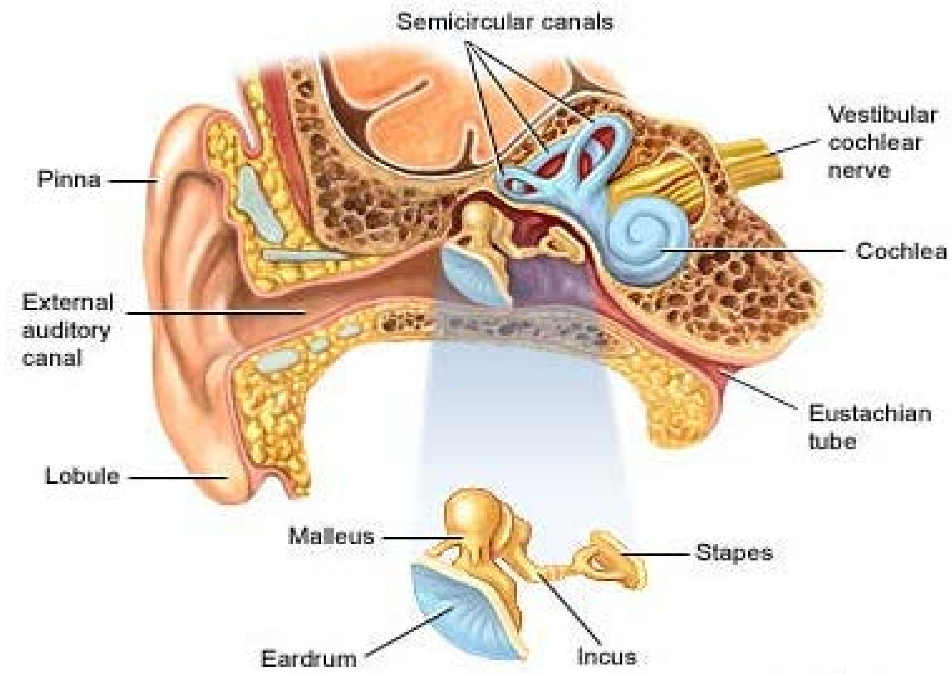

Figure 2.1. The hearing system in human. (Source: Netter's Atlas of anatomy)

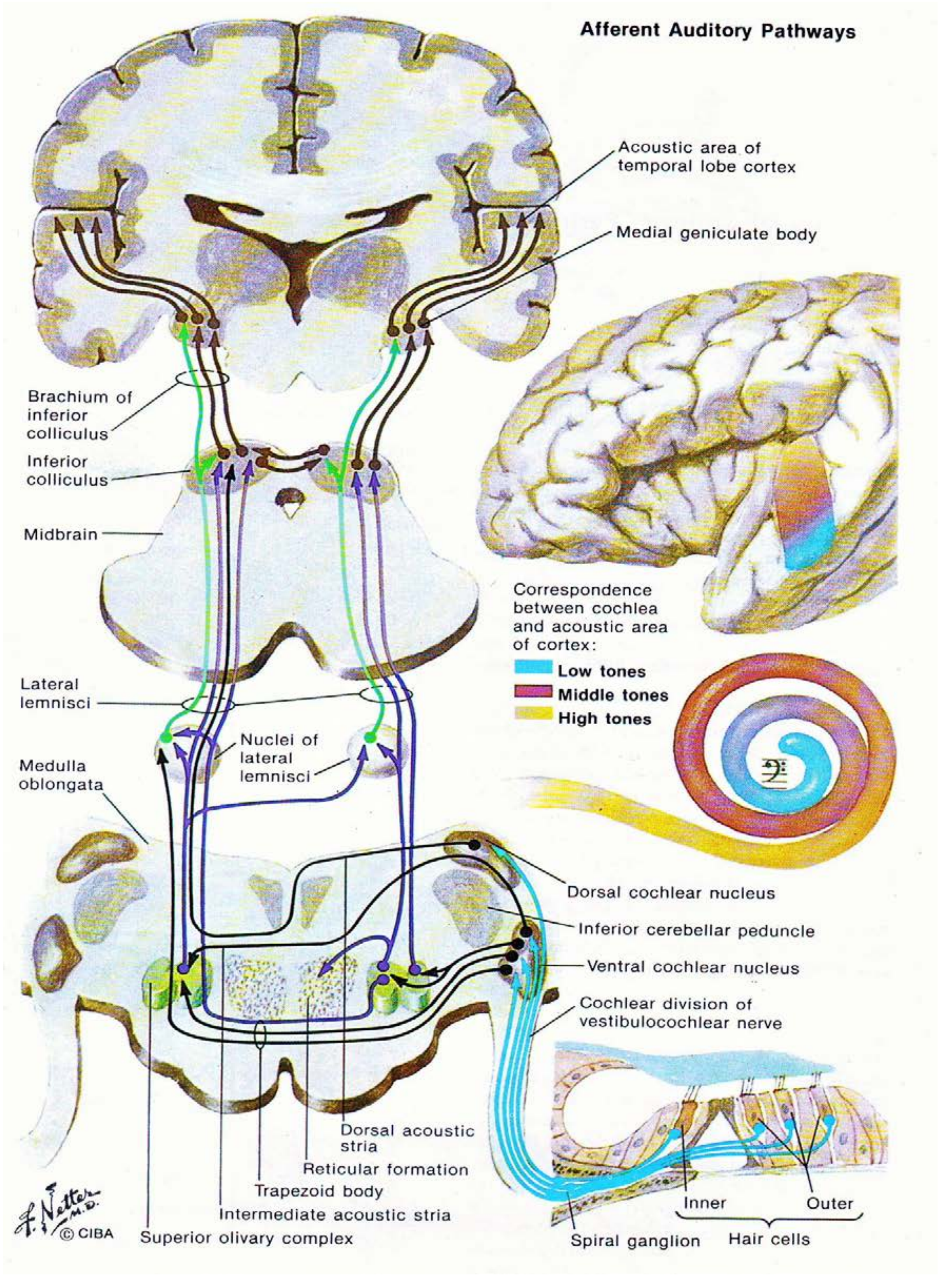

Figure 2.2. Diagram of central auditory nervous system. (Source: Netter's Atlas of anatomy)

The hearing system enables human for hearing sounds in the range frequency of 20 to 20,000 Hz. It also provides sensitivity for hearing the soft sounds about 0 dB

Sound Pressure Level (SPL) (which is the amplitude of vibration of about the size of a hydrogen molecule) to roughly 140 dB (at which pain and damage to the auditory mechanism can occur) (Gelfond, 2005).

2.2 Hearing loss and its consequences

When the hearing system is intact and works ideally, good hearing and normal hearing thresholds are expected. In the presence of disorders affecting any part of the hearing system, hearing loss can occur. Hearing loss is typically divided into threetypes. When the hearing disorder is located in the external or middle ear, it is called conductive hearing loss. Meanwhile, if there is a disorder in the cochlea or auditory nerve, the hearing loss is called sensorineural. Specfically, the disorders in the cochlea and auditory nerve are called sensory and neural loss, respectively. If there are co-existence disorders in the conductive and sensory parts of the hearing system, it can cause a mixedhearing loss. Additionally, hearing loss can also occur due anatomical or functional problems in the CANS. This uncommon type of hearing loss is called central deafness.

There are some differences among the different types of hearing losses, but a common phenomenon is reduction in hearing sensitivity which determines the level of hearing handicap. For instance, a patient with severe hearing loss shows speech problems, language retardation and learning dysfunction that are worse than a patient with mild hearing loss. On the other hand, due to specific disorders affecting the CANS, some patients may show reduction in speech intelligibilitydespite having normal hearing thresholds. Tables 2.1 and 2.2 show the grading of hearing loss and classification of hearing handicap as a function of average hearing threshold level, respectively (Roser, 1996).

Table 2.1. Classification of hearing impairment in relation to communication difficulty. (Audiology Diagnosis, Roser et al., 1996)

Level of hearing loss based on PTA (500, 1000, 2000 Hz)	*Degree of hearing loss*	*Effects of hearing loss*
26 to 40	Mild	Demonstrates difficulty understanding soft-spoken speech; needs preferential seating and may benefit from speechreading training; good candidate for a hearing aid.
41 to 55	Moderate	Demonstrates an understanding of speech at 3 to 5 feet; requires amplification, preferential seating, speechreading training, and speech therapy.
56 to 70	Moderate to Severe	Speech must be loud for auditory reception; difficulty in group and classroom discussion; may require special classes for hearing-impaired, plus all of the above needs.
71 to 90	Severe	Loud speech may be understood at 1 foot from ear; may distinguish vowels but not consonants; requires classroom for hearing-impaired and mainstreaming at a later date.
91+	Profound	Does not rely on audition as primary modality for communication; may work well with total communication approach; may eventually be mainstreamed at higher grade levels.

SOURCE: With permission from Goodman, A. (1965), "Reference zero levels for pure tone audiometers," *Asha* 7:262–263-1965.

Table 2.2. Classification of Hearing handicap as a function of average hearing thresholdlevel of the better ear. (Audiology Diagnosis, Roser et al., 1996)

Average threshold level at 500–2000 Hz (ANSI)	*Description*	*Common causes*	*What can be heard without amplification*	*Degree of handicap (if not treated in first year of life)*	*Probable needs*
0–15 dB	Normal range		All speech sounds	None	None
16–25 dB	Slight hearing loss	Serous otitis, perforation, monomeric membrane, sensorineural loss, tympanosclerosis	Vowel sounds heard clearly, may miss unvoiced consonant sounds	Possible mild or transitory auditory dysfunction Difficulty in perceiving some speech sounds	Consideration of need for hearing aid Lip reading Auditory training Speech therapy Preferential seating Appropriate surgery
26–40 dB	Mild hearing loss	Serous otitis, perforation, tympanosclerosis, monomeric membrane, sensorineural loss	Hears only some of speech sounds—the more loudly voiced sounds	Auditory learning dysfunction Mild language retardation Mild speech problems Inattention	Hearing aid Lip reading Auditory training Speech therapy Appropriate surgery
41–65 dB	Moderate hearing loss	Chronic otitis, middle ear anomaly, sensorineural loss	Misses most speech sounds at normal conversational level	Speech problems Language retardation Learning dysfunction Inattention	All of the above plus consideration of special classroom situation
66–95 dB	Severe hearing loss	Sensorineural loss or mixed loss due to sensorineural loss plus middle ear disease	Hears no speech sound of normal conversations	Severe speech problems Language retardation Learning dysfunction Inattention	All of the above; probable assignment to special classes
96+ dB	Profound hearing loss	Sensorineural loss or mixed	Hears no speech or other sounds	Severe speech problems Language retardation Learning dysfunction Inattention	All of the above; probable assignment to special classes

SOURCE: With permission from Northern, J.L., and Downs, M.P., *Hearing In Children*, 4th ed. Baltimore: Williams & Wilkins, 1991, page 99

2.3 Determining the type and level of hearing loss

In regard to the effects of hearing loss on communicational, social and educational skills, it is very important for identifying hearing loss at early stages, especially in neonates and children. There are many studies and publications regarding the importance of early identification and early intervention (Davis, 2014; Ptok, 2011; White, 2004; Marschark, 1998; NIH of USA, 1993).

> "*Babies with hearing loss who are identified early and provided with appropriate intervention develop better language, cognitive, and social skills."*(White, 2004).

The following lines show the importance of early identification and intervention:

> *"The primary justification for early identification of hearing impairment in infants relates to the impact of hearing impairment on speech and language acquisition, academic achievement, and social/emotional development.* ***The first 3 years of life are the most important for speech and language acquisition.*** *Consequently, if a child is hard of hearing or deaf at birth or experiences hearing loss in infancy or early childhood, it is likely that child will not receive adequate auditory, linguistic, and social stimulation requisite to speech and language learning, social and emotional development, and that family functioning will suffer. The goal of early identification and intervention is to minimize or prevent these adverse effects."* (National Institute of Health of USA, 1993).

> *"Early detection of hearing loss and early use of hearing aids or cochlear implants are critical for the development of speech, language, and communication skills in children with hearing loss. In fact, infants identified with a hearing loss before the onset of the critical period of language development around six months of age who* ***received a hearing aid or cochlear implant*** *and* ***habilitation services*** *have been shown years later to*

have language skills similar to those of children of the same age who have normal hearing." (Duthey, 2013)

For evaluating hearing loss, many methods are now available. These methods are classified into two types: subjectiveand objective hearing tests.

2.3.1 Subjective audiological assessments

These methods are designed for evaluating hearing based on the patient's cooperation. Pure tone Audiometry (PTA) and speech tests are examples of subjective audiological tests. PTA indeed is a phenomenon of hearing. It is a tool for measuring behavioural thresholds and regarded as the standard clinical hearing test. In PTA testing, the testerdetermined the hearing thresholds of audiometric frequencies based on the responses from the patients. In this regard, the tester must be skillful in doing the test so that the results will be valid. Since this test is highly subjective, if poor responses are obtained, the hearing test results will be invalid. This will be more prominent when testing neonates, younger children and those who are "difficult to test" (e.g. syndromic and multi-handicapped patients). This is when the objective hearing tests are useful for verifying the PTA results.

Speech tests (that use speech materials as stimuli) are beneficial to be conducted, particularly when the PTA results are questionable. The results of speech tests are also useful in hearing aid fitting process. There are two essential types of speech tests:

a) Speech reception threshold (SRT), which is carried out to determine the speech hearing threshold (for comparing with PTA result).

b) Speech discrimination score (SDS), which is conducted to determine the speech discrimination ability of subjects.

2.3.2 Objective audiological assessments

Objective tests offer a more convenient way to evaluate hearing as cooperation from patients are generally not required. In this type of testing, physiological and electrophysiological responses are recorded objectively. Some of these objective tests are used routinely in clinics for specific clinical applications including screening and diagnostic testing. Some of the common objective tests are as follows:

- Immittance Audiometry
- Otoacoustic Emissions (OAE)
- Electrocochleography (EcochG)
- Auditory Brain Stem Response (ABR)
- Auditory Steady State Response (ASSR)
- Auditory Middle Latency Response (AMLR)
- Auditory Late Response (ALR)
- Event Related Potentials (ERPs)
- Mismatch Negativity (MMN)
- Brain Mapping

2.3.2.1. Immitance Audiometry

It is a test for evaluating the middle ear and Eustachian tube function and acoustic reflex of stapedius muscle. These tests help in the diagnosis of hearing disorder, particularly the type of hearing loss.

2.3.2.2. Otoacoustic Emissions (OAE)

OAE is a low- level sound emitted by the cochlea, either spontaneously or evoked by an auditory stimulus. Specifically, it measures the function of outer hair cells of the cochlea (Stach, 1997). It has been used widely in audiology clinics for various clinical applications. It has three types: transient evoked otoacoustic emission

(TEOAE), distortion product otoacoustic emission (DPOAE) and stimulus frequency otoacoustic emission (SFOAE).

2.3.2.3. Auditory Brainstem Response (ABR)

Auditory brainstem response is used to predict hearing sensitivity and to assess the integrity of Cranial Nerve VIII and auditory brainstem structures (Stach, 1997). ABR is an electrical response which is evoked by an abrupt stimulus and recorded by electrodes on the scalp. Historically, it was initially used for detecting neural disorders and its application has expanded to estimating of hearing threshold and hearing screening purposes.

2.3.2.4. Auditory Steady State Response (ASSR)

The ASSR was first described in the 1980s and it has used widely for clinical applications. Due to its objectivity, it has emerged as a clinically valuable electrophysiological measure of auditory sensitivity at audiometric test frequencies over the range of 500 to 4000 Hz and across the intensity range of 0 to as high as 120 dB HL.

2.3.2.5. Auditory Middle Latency Response (AMLR)

The auditory middle latency response is observed in a time period between about 12 and 50 ms, a time frame that is after the ABR and before the auditory late response (ALR), thus the term “middle latency” is used (Hall, 2007). Auditory middle latency response (AMLR) is an auditory evoked potentials originating from the region of the auditory radiations and cortex, having as a primary component a vertex positive peak at 25 ms to 40 ms following signal presentation (Stach, 1997). It is used for finding lesions in CANS and for assessing hearing threshold.

2.3.2.6. Auditory Late Response (ALR)

Auditory late response (ALR) consists of responses recorded in a time period of 50 to 400 ms following the acoustic stimulation. It measures the integrity of theauditory cortex (Hall, 2007). It has two prominent main peaks: N1 (the first negative peak, occurs around 100 ms) and P2 (the second positive peak, occurs around around 150 to 200 ms). It is also used for estimating hearing thresholds at specific frequencies. In fact, changes in P1 (peak of AMLR), N1, and P2 components of the ALR have been found following the auditory training (Hall, 2007).

2.3.2.7. Event Related Potentials (ERPs)

Different from other types of electrophysiological tests, in order to record ERPs, tone bursts or speech stimuli must be presented in oddball paradigms. ERPs are highy related to the perceptions of auditory stimuli (e.g. discrimination and attention). It has many subtypes including mismatch negativity, P300, N400 and P600 which are related to discrimination, attention, semantic and syntax, respectively (Hall, 2007).

2.3.2.8. Mismatch Negativity (MMN)

The MMN was discovered by Naatanen in 1978. It is a subtype of ERP and believed to measure theauditory discrimination ability. The MMN can be evoked by using subtles differences in the main features of auditory stimulus including pitch, duration or loudness. It can also be evoked by deviation in the locus of regular stimulus. The MMN is not dependent on attention, so it can be recorded during sleep and in newborns (Martynova, 2003).

2.3.2.9. Brain Mapping

In the late 1970s, a new way for analyzing evoked responses was introduced in clinical neurophysiology. One of the pioneers in this field was Frank Duffy, a neurophysiologist. In 1979, he pioneered the technique for computerized topographic evoked response analysis, known as "brain electrical activity mapping, or BEAM". Nowadays, "brain mapping" or "topographic mappings" are the terms often used to describe the computerized evoked response topography. In this method, the recorded waveforms are convertedinto three dimension maps with specific colors.

2.4. Speech-evoked Auditory Brainstem Response (sABR)

After using ABR as a clinical tool for testing the hearing system, it was almost a dream to use speech stimuli for recording responses of brainstem. Recording ABR with speech stimuli is called sABR.Even though both click-evoked ABR and sABR are generated by brainstem, but their specific generators are different (Song et al. 2006). In some studies, since sABR shows auditory brainstem responses to complex sounds, it is also known as complex ABR (cABR). Chandrasekaran and Kraus (2010) stated that the term cABR is used to describe both the transient and sustained responses originating in the auditory brainstem response. Nowadays, a plethora of complex stimuli has been used to examine how the temporal and spectral features of sounds are preserved in the ABR. The use of complex stimuli provides more sensitivity than do clicks or tone bursts to subtle differences in impaired populations, relative to normal controls (Song et al., 2006), thus highlighting the potential for the sABR to provide an effective means of assessing central auditory system function.

Music, complex tones, and speech stimuli (e.g., /da/, /ba/, and /ga/) have been used to elicit sABR. A speech stimulus is particularly useful as it can provide clues as how the temporal and spectral features are processed in the brainstem (Skoe & Kraus, 2010). Early works on sABR focused on syllable /da/ (Cunningham et al., 2001; Russo et al., 2004), an acoustically complex sound, which begins with a stop burst, characterized by an non-harmonic and broadband frication, followed by a harmonically rich and spectrally dynamic formanttransition (Figure 2.3).Maddieson (2010) state that the /da/ stimulus is a universal syllable that is included in the phonetic inventories of most European and Asian languages. The syllable /da/ consists of transientsegment; stop burst which is similar to the click-evoked ABR followed by sustained periodic segment; which is similar to tone-evoked frequency following response (FFR).

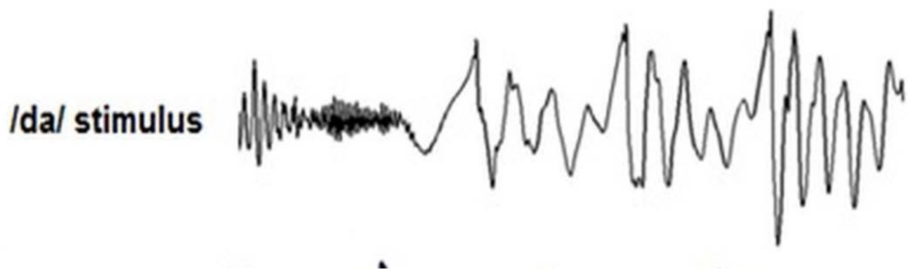

Figure 2.3. Waveform of 40-ms syllable [da] synthesized in a Klatt-based synthesizer. (Skoe & Kraus, 2010)

The acoustical property of /da/ is similar to click stimulus followed by a tone- two acoustic signals whose brainstem response properties have been extensively characterized. Then, stop consonants pose great perceptual challenges to clinical populations such as the hearing and learning impaired (Tallal & Stark, 1981; Turner et al., 1992; Kraus et al., 1996). However, because stop bursts are rapid and low in amplitude compared to vowels, even normal-hearing adults and children can find it difficult to discriminate between contrastive stop consonants (e.g., "*d*are" versus "*b*are") in noisy environments.

Hornickel and Kraus (2012) state that sABR is an objective assessment of biological process underlying the auditory processing deficits and auditory function which cannot be revealed by using click stimulus. Responses from both click ABR and sABR are recorded in the same fashion except that the speech stimuli are longer in duration, more temporally and spectrally dynamic than that of click stimulus.

Other types of sounds including environmental sounds, affective non-speech vocal sounds (e.g. baby’s cry) and musical sounds have been reported to be viable stimuli for brainstem-evoked recordings. Works on music-evoked ABRs have included a bowed cello note (Musacchia et al., 2007, 2008), a five-note musical melody (Skoe & Kraus, 2010), as well as consonant and dissonant two-note intervals synthesized from an electric piano (Lee et al., 2009) and tone complexes (Greenberg et al., 1997; Bidelman & Krishnan, 2009). From the same study carried out by Hornickel and Kraus (2012), they found that the speech stimulicontained complex cues including timing, harmonic and pitch. Skoe and Kraus (2010) stated that complex sounds are rich in harmonic structures, dynamic amplitude modulations, and rapid spectro-temporal fluctuations and this complexity is represented by an exceptionally precise temporal and spectral neural code within the auditory brain stem, which ensemble of nuclei belonging to the efferent and afferent of auditory systems.For complex stimuli, the two most extensively studied stimuli are the consonant-vowel (CV) syllable /da/ (Cunningham et al,. 2001; Plyler & Ananthanarayan, 2001; King et al., 2002; Russo et al., 2004, 2005; Wible et al., 2004, 2005; Kraus & Nicol, 2005; Musacchia et al., 2007; Johnson et al., 2008a; Banai et al., 2009; Burns et al., 2009; Parbery-Clark et al., 2009; Hornickel et al.,2009b; Chandrasekaran et al., 2009) and Mandarin syllables with differing pitch contours (i.e., lexical tones) (Krishnan et al., 2004, 2005, 2009b; Xu et al., 2006; Wong et al., 2007; Song et al., 2008; as reviewed by Krishnan & Gandour, 2009).

Other than the stimulus issues, ABR to /da/ stimulus has been investigated under different recording conditions: monaural (Cunningham et al., 2001; Banai et al., 2009) and binaural (Musacchia et al.,2008; Parbery-Clark et al., 2009) stimulation; left ear and right ear stimulation (Hornickel et al., 2009a); audiovisual and auditory only stimulation (Musacchia et al., 2006, 2007); and in the presence of background noise (Cunningham et al., 2001; Russo et al., 2004, 2005, 2008; Parbery-Clark et al,. 2009). Hornickel et al.(2009) stated that the auditory brainstem functions can also be changed or shaped via lifelong experiences to sound such as playing music and speaking multiple languages. Knowing the neural processing at the brainstem level may increase understanding on the outcomes in individuals with hearing loss, language disorders and learning deficits (Carter, 2013). Hornickel and Kraus (2012) also believed that timing and harmonic are important cues for an individual to identifywhich speech sounds are spoken while the pitch cues are important to identify the identity of the speaker. All these three cues are linked to the auditory based communication skills such as reading and speech in noise. The reading skills are related to the response in timing and harmonic while the speech in noise is related to the pitch encoding. Thus, by performing the sABR, we can predict the individual's reading skills and speech in noise perception.

According to the Skoe and Kraus (2010), the transient responses are the fast response peaks lasting fractions of milliseconds that are evoked by brief, unstable features of stimulus such as the onset and offset parts of sounds. In the case of speech syllables, the onset of vocal cord vibrating (i.e., voicing) is also included in the transient features. Skoe and Kraus (2010) also stated that the onset of the sABR morphology is dictated by the attack characteristics (i.e., how quickly the sound reaches the full volume) of the specific acoustic token. Stimuli with sharper rise times are more broadband, less frequency specific, and cause broader and more simultaneous activation of cochlea, which enlists a larger population of neurons to fire synchronously and leads to more robust transient response. The obstruent stop consonants (e.g., /d/, /p/, /k/) have, by definition sharper and produce more robust onset response. In addition, for both speech and music, attack characteristics are important for imparting timbre (sound quality) and they contribute to the identification of specific speech sounds (Rosen, 1992) and instruments (Grey, 1977; Howard & Angus, 2001). Sustained features, according to the Skoe and Kraus (2010), are soundscontaining continuous acoustic features such as sinusoidal tones, harmonically complex vowels, and musical notes reflecting synchronous population-wide neural phase-locking. The first person to describe the sustained response in human by using scalp-recorded brainstem potentials was Moushegian et al. (1973). In their study, sinusoids ranging from 250 to 2000 Hz were used and they demonstrated that each frequency evoked a unique response in which the pattern of neural discharge was time locked to the temporal structures of the eliciting sounds.

Many clinical aspects of sABR have been investigated including sABRs to /da/ before and after auditory training (Russo et al., 2008b; Song et al, 2008); at different age (Johnson et al., 2008b; Burns et al., 2009; Anderson et al., 2010); and in a number of different populations including musicians (Musacchia et al., 2007, 2008; Parbery-Clark et al., 2009) and children with dyslexia, specific language impairment, and autism spectrum disorders (Cunningham et al., 2001; Banai et al., 2005; Banai &Kraus, 2008; Banai et al., 2009; Hornickel et al., 2009b; Chandrasekaran et al,. 2009; Russo et al., 2009).