# Automatic Detection of Selective Auditory Attention Via Transient Evoked Otoacoustic Emissions

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science

Graduate Department of Electrical and Computer Engineering University of Toronto

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# Abstract

Past studies have shown that the effects of selective auditory attention are evident in medial olivocochlear (MOC) activity, manifested as the contralateral suppression (CS) of transient evoked otoacoustic emissions (TEOAEs). This finding suggests the use of TEOAEs in the design of an auditory-based access technology as a potential access solution for children with severe disabilities. Thirteen participants with normal hearing threshold and normal middle ear function completed this study. The participants were instrumented with a TEOAE ear probe and presented with a contralateral acoustic stimulus. They were instructed to alternate auditory attention conditions as visually cued by symbols on an LCD display. Attentive and non-attentive conditions were detected with an overall accuracy of  $70.17\pm12.54\%$  at  $2.44\pm0.3$  bits minute<sup>-1</sup> in a participant-specific classifier, and  $65.92\pm13.91\%$  in a participant-independent classifier.

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# List of Abbreviations

Symbol	Description			
CAS	Contralateral Acoustic Stimulus			
CN	Cochlear Nerve			
CS	Contralateral Suppression			
daPa	Deca-pascal			
dB	Decibel			
EOAE	Evoked Otoacoustic Emission			
GUI	Graphical User Interface			
HT	Hilbert Transform			
IHC	Inner Hair Cell			
LCD	Liquid Crystal Display			
LDA	Linear Discriminant Analysis			
MOC(S)	Medial Olivocochlear (System)			
MSOC	Medial Superior Olivary Complex			
OAE	Otoacoustic Emission			
OCB	Olivocochlear Bundle			
OHC	Outer Hair Cell			

peSPL	Peak Equivalent Sound Pressure Level
RMS	Root Mean Square
SNR	Signal to Noise Ratio
SPL	Sound Pressure Level
TEOAE	Transient Evoked Otoacoustic Emission
UOCB	Uncrossed Olivocochlear Bundle
WPT	Wavelet Packet Transform

# Chapter 1

# 1 Introduction

# 1.1 Clinical Problem

Many individuals with severe physical disabilities face challenges with communication and control of their surrounding environment due to verbal and motor impairments. These severe physical disabilities include brain stem stroke, neurodegenerative disorders such as multiple sclerosis, neuromuscular conditions such as muscular dystrophy, high level spinal cord injuries, and acquired brain injuries. Their inability to physically interact with the environment motivates the search for a suitable solution to translate a mental state (functional intent) that can be interpreted by means of technology into a task that the individual wishes to achieve (functional activity). The detection of a functional intent enables an individual with a severe physical disability to activate a switch. The search for such an access solution is important because it can improve the quality of life of individuals with severe physical disabilities by increasing their level of independence [1, 2]. Specifically, for children with severe physical disabilities, an access solution enables them to participate in the educational curriculum and enhances social interaction [3]. A significant fraction of the 84,280 Canadian children with severe to very severe disabilities as reported in the 2006 Participation and Activity Limitation Survey [4], are affected by a lack of access to communication and environmental control.

# 1.2 Access Technology

The framework (Figure 1) in [5] defines an access solution as a system which converts functional intentions into functional activities. The access technology in the context of an access solution consists of an access pathway which receives sensor inputs from the user and a signal processing algorithm which translates sensor data into control signals.

Access technologies can be categorized by the input approaches: biomechanical means and physiological signals. Examples of access technologies that process functional movement are button switches, lever switches and computer vision switches. However, individuals who lack



#### Figure 1: An access solution (Source [5]).

active motor movement must resort to access technologies that utilize physiological signals. Examples include electroencephalography (EEG), electrocorticography (ECoG), intracortical recordings, and near-infrared spectroscopy (NIRS). Generally, motor movement-based switches are preferred over access technologies that harness physiological signals, in terms of reliability and usability.

### 1.3 Auditory-based Access Pathways

Auditory-based access pathways can be a solution that enables individuals to express thoughts without vocal control or active motor movement. Research on auditory-based access pathways has primarily focused on brain-computer interfaces that decipher intention by interpreting brain activity associated with attention-related auditory tasks. In particular, auditory tasks have been noninvasively detected via functional magnetic resonance imaging [6, 7] and electroencephalography, namely, the P300 evoked potential [8, 9, 10, 11, 12], and sensory motor rhythms [13]. Solutions proposed to date are either not portable, susceptible to electrophysiological interference, or too complex to be set up or maintained by caregivers.

While auditory-based intent as manifested in brain signals has been previously investigated, access technology research has not yet explored the detection of auditory attention through the auditory peripheral nervous system. The review of transient evoked otoacoustic emission (TEOAE) technology and human auditory physiology as related to auditory attention, has suggested a new direction for the design of an auditory-based access technology. Neural

activities mediated by the olivocochlear bundle reflect intentional changes in selective auditory attention. The olivocochlear reflexes modulate the outer hair cells' mechanical vibrations, which can be indirectly measured by TEOAEs. Intents thus can be converted into control signals for binary communication via TEOAEs (i.e., attentive and non-attentive). This novel access pathway may offer greater portability and simpler sensor set-up than other existing technologies sensitive to auditory attention.

# 1.4 Objective

The objective of this thesis was to design a system to differentiate between an attentive and a non-attentive auditory condition via TEOAEs. In the context of access technology, this work naturally led to the research question:

At what level of accuracy, can auditory attention be detected with a TEOAE-based access pathway?

As an initial exploration of TEOAE as an access pathway, it should be noted that the goal was not to search for an optimal protocol design, but to explore signal processing algorithms that facilitate detection of a desired mental state (i.e., an attentive auditory condition) at accuracies that are higher than random chance and comparable to those achievable with other auditorybased access pathways.

# 1.5 Roadmap

Based on the initial review of TEOAE technology and its history in research, this thesis adopted a particular protocol design. Specifically, a contralateral acoustic stimulus (CAS) with tone bursts embedded in broadband noise was designed as the attention target of an auditory task for the user. The broadband noise had temporally alternating intensity to enable measurements of a physiological effect in the ipsilateral ear via TEOAEs. The performance of the design with a number of different signal processing algorithms was evaluated.

The remainder of the thesis is organized as follows.

Chapter 2 introduces TEOAE technology and gives a brief description of its mechanics and clinical applications. It also presents the physiology of the medial olivocochlear bundle and explains the current understanding of TEOAE in the study of selective auditory attention.

Chapter 3 details a research study investigating a TEOAE-based access pathway with 17 ablebodied participants. This chapter describes the experimental design, the experimental protocol, and a method that empirically evaluates the performance of a detection algorithm with a number of candidate features for selective auditory attention.

Chapter 4 reports the results of the research study and discusses the performance of the detection algorithm using the proposed features.

Chapter 5 discusses limitations of the research study, specifically, internal and external factors that may have affected detection performance.

Chapter 6 concludes this thesis with a summary of contributions.

Appendix A documents the use of the TEOAE instrumentation that is specific to this research.

Appendix B reports on a pilot test for the possible confounding effect of visual attention on TEOAEs.

### Chapter 2

# 2 Background

# 2.1 Transient Evoked Otoacoustic Emissions

Transient evoked otoacoustic emission (TEOAE) is sound generated by the cochlea in response to transient acoustic stimulus (e.g., a click sound). TEOAEs are acquired by a probe that consists of a speaker and a microphone. Click stimuli are delivered to the ear by the TEOAE probe in an occluded ear canal to produce recordable sound pressure up to a frequency of 6 kHz. The middle ear efficiently provides coupling between the tympanic membrane and the stapes with the analogy of a bidirectional horn that both enhances hearing as well as amplifying sound in the reverse direction [14]. Thus, sound generated by the cochlea returns to the ear canal as TEOAE, amplified by the ossicles, with a latency of 1 millisecond. TEOAEs are typically recorded by a microphone in a time window following each click stimulus (Figure 2).

TEOAEs are formed as a result of the active process of the cochlea. Measurable TEOAEs are caused by the energy diverted from the primary hearing process, the pressure





difference created by the transmission of energy back to the cochlea, and the amplification of

acoustic energy through the middle ear. The source of this energy working in reverse is believed to be the electromotility of the outer hair cells, which has been indirectly measured via TEOAEs. This active process is also known as the active "cochlear amplifier".

Three phenomena contribute to the formation of TEOAEs.

- When the forces exerted by the outer hair cells on the basilar membrane do not exactly follow the stimulus waveform, distortion signals are introduced into the returned vibrational energy.
- Spatial imperfection of the outer hair cells (i.e., non-uniform distribution of OHC motility) amplifies fluid waves at some locations of the basilar membrane and thus may result in the generation of stimulus frequency OAEs [15, 16].
- 3. Energy in the cochlear compression fluid waves escape from the round window and reenters the cochlea through the oval window. This positive feedback loop can repeatedly stimulate the OHCs and lead to spontaneous OAEs [17, 18].

TEOAEs are highly nonlinear and nonstationary. The cochlea has a tonotopic organization. High frequency sounds up to 20 kHz are processed at the base of the cochlea. Sounds at low frequencies down to 20 Hz are processed at the apex of the cochlea. Consequently, cochlear responses are returned to the ear canal at different times for different frequencies. Frequency analysis of TEOAEs is normally performed at frequencies up to 6 kHz, as TEOAEs are normally strongest between 1 and 6 kHz (Figure 2).

While TEOAEs cannot be used for the diagnosis of sensorineural hearing loss, their presence is a strong indicator of cochlear health. TEOAE measurement is commonly used in neonatal hearing screening because conventional testing methods are not suitable for this population. Recently, TEOAEs have been considered for their biometric potential [19]. Given the documented and measurable effect of attention on the olivocochlear bundle by way of TEOAEs, this thesis investigates the TEOAE as an access pathway for individuals with severe physical disabilities.

# 2.2 Medial Olivocochlear Bundle and Selective Auditory Attention



Selective auditory attention is achieved through higher processing of sounds in the auditory cortex. Brain activity related to auditory attention is mediated via the medial

olivocochlear (MOC) efferents. MOC efferents are thick, myelinated auditory nerve fibres that originate in

the medial superior olivary complex and synapse the outer hair cells (OHCs). The uncrossed portion of the MOC efferents can be activated by acoustically stimulating the contralateral ear. Signals travel through the auditory reflex interneurons of the contralateral cochlear nucleus, ventrally across the brainstem to the uncrossed olivocochlear neurons, down to the ipsilateral cochlea and the outer hair cells (Figure 3). During an activation of the MOC efferents, acetylcholine is released from the MOC terminal, diffuses across the synaptic cleft, and opens a channel to allow calcium entry to the OHCs. Depolarization occurs as a result. The influx of calcium ions to the OHCs can cause both fast and slow MOC effects. Fast MOC effects occur with outflow of potassium through the calcium-activated potassium channels on a time scale of hundreds of milliseconds, whereas slow MOC effects occur with OHC stiffness changes on a time scale of tens of seconds. MOC effection of signals in noise, which aids in the performance of processing transients of sound waves such as speech [20, 21, 22]. A detailed explanation of the MOC anatomy and physiology can be found in [23, 24].

Activations of MOC efferents can be measured in TEOAEs. Modulation of MOC efferents can be activated by acoustically stimulating the contralateral ear with broadband noise. Signals travelling from the inner hair cells (IHCs) to the cochlear nucleus through the auditory nerve are sent to the medial superior olivary complex for the measurement of interaural time difference. This mechanism is believed to play a role in sound localization. The uncrossed MOC efferents

# Figure 3: Anatomy of MOC efferents (Adapted from source [23])



decreases TEOAE levels in the ipsilateral ear. This reduction is known as the contralateral suppression (CS) of TEOAEs [25, 26, 27, 28]. The effect of selective auditory attention on TEOAEs has been demonstrated in past research

[29, 30]. Some studies have used contralateral acoustic stimulation to show a significant effect of auditory

Figure 4: An illustration of the signal pathways that lead to an increase in OHC activity and a decrease in TEOAE levels (Source [43]).

attention on the CS of TEOAEs [21, 31, 32, 22]. The presence of this effect strongly supports the hypothesis that auditory attention modulates TEOAE responses by overriding the acoustic reflexes in the MOC efferents. Further, the focus of auditory attention on a specific tone causes a frequency-specific variation of TEOAE as tested in a study using contralateral acoustic stimulation [33]. However, the difference in patterns is highly dependent on the set-up of the test conditions. This measurable effect of auditory attention on TEOAEs may be used towards the design of an auditory-based access technology.

mediate some of this activity to the OHCs (Error! Reference source not found.), which

TEOAE as a candidate access pathway presents several advantages over existing solutions sensitive to selective auditory attention (e.g., electroencephalographic detection of auditory steady-state responses). TEOAE instrumentation is non-invasive and portable, and requires only a single-sensor set-up for signal acquisition. Further, the equipment and associated consumables are less expensive than that required for evoked potential measurement. On the other hand, at present TEOAE measurements must be made amid controlled acoustic conditions and with minimal subject movement.

# 2.3 Possible Cross-modal Visual Attention Effect on TEOAEs

Early studies of attention and TEOAEs suggested that visual tasks had cross-modal effects on the auditory descending pathway. Froehlich et al. [34] demonstrated the repeatability of significant

decreases in TEOAE amplitudes during visual tasks for some participants by randomly presenting one of two letters on television and instructing the participants to count the occurrence of one letter. Their findings were supported in a subsequent study using visual flashes [29]. Decreases in TEOAEs during visual attention were later demonstrated specifically in a group of individuals without spontaneous OAEs [35]. The effect of visual attention on the CS of TEOAEs was studied by [36]. However, [31] found no significant differences between a no-task condition and visual attention conditions, possibly due to low visual task complexity. The experimental design of the study in this thesis used a simple visual task as a cue to alternate between an attentive and a non-attentive auditory condition. In Appendix B, TEOAE recordings under a similar experimental design as the current research study and their data analysis confirmed de Boer's findings [31] of no significant effects on CS of TEOAEs.

### Chapter 3

# 3 Research Study

# 3.1 Research Ethics

This study was approved by Bloorview Research Institute Research Ethics Board (file number: 11-233) and University of Toronto Research Ethics Board (protocol number: 26852). All participants were informed about the study prior to screening and data collection. All participants provided written consent.

### 3.2 Participants

Seventeen able-bodied adult participants were recruited. Thirteen participants completed the study (3 M, 10 F, ages  $30.4 \pm 7.8$  years). Participants that completed the study had normal or corrected-to-normal vision, normal hearing thresholds, and normal middle ear functions. Normal hearing threshold is defined as less than 20 dB HL for octave frequencies between 0.25 and 8 kHz. Normal middle ear function is defined as middle ear pressure between -150 and 100 daPa with a compliance value between 0.3 and 1.6ml. Participants were assessed by an audiologist at Holland Bloorview Kids Rehabilitation Hospital during screening sessions.

### 3.3 Experimental Design

#### 3.3.1 Contralateral Acoustic Stimulus

A Contralateral Acoustic Stimulus (CAS) was designed and applied to the contralateral ear of the participant for two purposes:

(1) Activate the MOC efferent and enable observations of the CS of TEOAEs, and

(2) Design a sound which the participant could focus auditory attention even when embedded in noise.



**Figure 5: The setup of the experiment.** 

The CAS was produced by a custom made program in Matlab and delivered to the ear with an earphone of frequency range between 20 Hz and 20 kHz. It consisted of white broadband noise (20 to 10000 Hz) alternating between 55 and 70 dB SPL at a period of 4 seconds. A 20-millisecond 1 kHz tone burst was embedded in the broadband noise near the hearing threshold (i.e., -10 to -15 dB SNR with tone bursts as signals and broadband noise as reference) with a probability of 75% for one tone burst per second. To estimate hearing thresholds, participants were tested with embedded 1 kHz tone bursts in noise varying from -8 to -14 dB SNR. The CAS was calibrated at 0.5 to 1 dB SNR above the threshold for each participant. An attentive condition was defined as a state in which the participant is explicitly following and counting tone bursts. A non-attentive condition is defined as a state in which the participant is not following or counting tone bursts (i.e., a "rest" state).



Figure 6: The participants were instrumented in a quiet room with TEOAE measurements in the right ear and CAS in the left ear, along with industrial sound protected ear muffs. CAS was sent to the ear by Computer 1 with an earphone. TEOAEs were acquired by Vivolink and sent to Computer 2 via bluetooth communication.

# 3.3.2 TEOAE Instrumentation

TEOAEs were acquired with the Vivosonic Integrity V500 System (Appendix A) from the ipsilateral ear for the detection of visual attention. Non-linear click stimuli of 80 dB peak equivalent sound pressure level (peSPL) to the ear at 80 microseconds per click and 47.35 clicks per second (i.e.,sweep-to-sweep time 21.12 milliseconds). TEOAEs were recorded at a post-stimulus time window between 2.8 and 12 milliseconds. Artifact rejection threshold was disabled to temporally align TEOAE data to the trials of the experiment. Industrial sound ear muffs with reduction of 30 dB SPL were used to minimize noise contamination of TEOAEs.





### 3.3.3 Experimental Protocol

Participants performed two sessions of auditory attention tasks. In the first session, the participants were informed of the procedure. They spent up to 30 minutes familiarizing themselves with the system and the auditory attention tasks. TEOAEs recorded in session 1 were not considered in the ensuing analysis. In the second session, the same auditory attention tasks were performed, with the TEOAE recordings collected for data analysis.



#### Figure 8: The protocol of TEOAE recording.

During each session, the participants were instrumented in a quiet room (Figure 5) with TEOAE measurements in the right ear and CAS in the left ear, along with industrial noise suppression ear muffs (Figure 6). Three TEOAE recordings were performed in each session with up to 5 minutes of rest between recordings. Each recording consisted of a 60-second pre-trial recording period, followed by 20 trials of auditory attention tasks. The purpose of the pre-trial period was to allow the TEOAE waveforms to stabilize. Each trial consisted of a time interval with either a non-attentive condition or an attentive condition. The participants were visually cued via an LCD (Figure 7) for the attention conditions. They were instructed to count the number of tone bursts occurring in the attentive condition periods and to record the count on paper at the end of each attentive condition period. Each time interval was assigned a random duration between 20 and 30 seconds (Figure 8), equivalent to  $2.44 \pm 0.30$  bits per minute.

#### 3.3.4 Data Collection

Three TEOAE sensor data sets, which included waveforms A and B (Appendix A) were recorded for each data collection session. Each of these waveforms was an average of a sequence of summed averaged signals of 12 alternate TEOAEs, with a post-stimulus time window between 2.8 and 12 milliseconds and a sampling rate of 38,400 samples per second. TEOAE data in the pre-trial recording period were removed before data analysis.

### 3.4 Detection Algorithms



#### Figure 9: Conversion of intent to binary output through pattern recognition methods.

In search of a detection algorithm, data were processed according to the typical stages of pattern recognition (Figure 9). TEOAE responses were recorded under an attentive or a non-attentive auditory condition. Data collected in each trial were used for preprocessing and feature extraction. Detection of auditory attention here was treated as a two-class classification problem. Seven features were compared in the evaluation of performance, where feature selection was required for multi-dimensional features with an exhaustive search.

#### 3.4.1 Pre-processing

Given that TEOAEs are typically strongest within a frequency range between 1 and 6 kHz, a second order Butterworth bandpass filter with cutoff frequencies at 750 Hz and 6 kHz was applied to each summed averaged TEOAE response in Waveforms A and B.

For features extracted using time frequency analysis methods, a low pass second order Butterworth bandpass filter with cutoff frequency at 6 kHz was applied to each summed averaged TEOAE response in Waveforms A and B, followed by a down-sampling to 12,000 samples per second.

The average waveform, computed based on the filtered and down-sampled responses, was the sum of the averages of Waveforms A and B,. This average waveform was used for feature extraction.

#### 3.4.2 Feature Extraction and Feature Selection

Two physiological processes were considered in the detection of selective auditory attention: outer hair cell activity and fast olivocochlear efferent activity. Seven feature extraction techniques were implemented to derive quantifications of the two physiological processes.

#### 3.4.2.1 Features as Measurements of Outer Hair Cell Activity

Early findings of TEOAE research indicated the possibility of OHC activity affected by selective auditory attention and consequent modulation of TEOAEs. [29, 30] observed decreased TEOAE amplitudes during auditory attention to tone bursts. Retrospect of experimental design and data collection, TEOAEs minus the effect of temporally alternating sound pressure levels of the CAS must be extracted from the raw data before feature extraction . As the two sound pressure levels of broadband noise in the CAS were designed with equal duration per period, each of the two CS levels of TEOAEs is expected to occur 50% of the time. In each trial, TEOAEs with RMS values below the median RMS were discarded. The ensemble average of the remaining TEOAEs was then used for the extraction of the following features.

#### Magnitude of TEOAE Responses

The magnitude of TEOAE responses (abbreviated as "OHC – RMS" in the subsequent chapters) was the RMS of the ensemble average.

#### Wavelet Packet Transform

Focused auditory attention on a specific sound in the CAS may activate the olivocochlear bundle and manifest as variation of the OAE amplitudes in a frequency specific way. Since TEOAEs are non-linear and non-stationary signals, feature extraction using time frequency analysis methods may enable extraction of attention-related information from the signals. Wavelet Packet Transform (WPT) was used here to enable an analysis of frequency specificity of selective auditory attention on TEOAEs. At each level, WPT decomposes a waveform into an approximate signal and a detail signal, dividing the frequency band into two halves for further analysis. The ensemble average of TEOAEs from each trial was used. With three levels of WPT and second order coiflets, the ensemble averaged TEOAE was decomposed into 8 waveforms, where each waveform covered a sub-band of 750 Hz across 6 kHz. An RMS value was calculated for each of the eight waveforms (Figure 10), forming an 8-dimensional feature (abbreviated as "OHC – WPT" in the subsequent chapters). Up to 4 dimensions were selected using an exhaustive search.



Figure 10: Feature using the energy in the decomposition of TEOAE to 8 frequency subbands, where A and D are the approximation and detail signals of WPT, and Y<sub>i</sub> is the energy of the TEOAE in the i-th frequency sub-band.

#### Time Window Analysis

TEOAEs as non-stationary signals potentially enable extraction of information in sub-time intervals of TEOAE responses. The ensemble average of TEOAEs from each trial was used and divided into five epochs of 1.84 milliseconds. An RMS value was calculated from each epoch, forming a five candidate features (abbreviated as "OHC – time window" in the subsequent chapters). Feature selection was performed to identify the most discriminatory feature.

### 3.4.2.2 Features as Measurements of Fast Medial Olivocochlear Efferent Activity

In the past decade, CS of TEOAEs was investigated as a metric of MOC activity. Studies related to selective auditory attention had a significant effect of selective auditory attention on CS [33, 31, 32, 22]. Three techniques were examined in extracting features related to CS of TEOAEs.

# Direct Computation of CS of TEOAEs

With the two temporally alternating CAS broadband noise sound levels, the lower TEOAE suppression level could be subtracted from the higher TEOAE suppression level in the

computation of the CS of TEOAEs. In each trial, TEOAEs were sorted in ascending order of their RMS values. The average energy in the TEOAEs of the subset with energy levels above the median RMS values is the suppression level at 55 dB SPL CAS broadband noise sound level. And the average energy in the TEOAEs of the subset with energy levels below the median RMS values is the suppression level at 70 dB SPL CAS broadband noise sound level. The difference between the two average energy levels was computed as a feature (abbreviated as "MOC – CS" in the subsequent chapters) that is representative of fast MOC efferent activity.

#### Discrete Time Analytic Signal Using Hilbert Transform

As the CAS was designed with sound pressure levels that alternated every two seconds, amplitude modulation of TEOAEs (i.e., CS of TEOAEs) was expected to occur at 0.5 Hz. The RMS values of TEOAEs were computed to form a time series,  $\mathbf{X}$ , with frequencies between 0 and 1.97 Hz. The cochlear response to the CAS is expected to give almost-square waveform characteristics in  $\mathbf{X}$ , whereby envelope extraction can be used to measure the CS of TEOAEs.

The complex magnitude values of the discrete time analytic signal were obtained using the

Hilbert transform of X, from which the envelope was estimated. This envelope extraction method

is useful for signals with narrowband frequencies. The analytic signal,  $\mathbf{X}$ , is written as:

### $\hat{X} = Re\{X\} + j\hat{X}$

#### Equation 1: Analytic signal using Hilbert transform.

where  $\tilde{X}$  is the discrete Hilbert transform of Re[X]. The discrete Hilbert transform can be obtained via the following steps [37]:

1. Compute the N-point FFT  $\mathcal{G}(m)$  from  $\mathcal{Re}[X]$  padded with zeros as needed

2. Form the N-point one-sided analytic signal transform

$$H(m) = \begin{cases} G(0), \text{ for } m = 0\\ 2G(m), \text{ for } 1 \le m \le \frac{N}{2} - 1\\ G(\frac{N}{2}), \text{ for } m = \frac{N}{2}\\ 0, \text{ for } \frac{N}{2} + 1 \le m \le N - 1 \end{cases}$$

#### Equation 2: One-sided analytic signal transform.

3. Compute the N-point inverse FFT of  $\mathbb{H}(m)$  to get  $\tilde{X}$ 

High level peaks of  $\hat{X}$  are indications of amplitude modulation of TEOAEs in response to change

in CAS broadband noise sound pressure levels. The RMS value of  $\mathcal{X}(n)$  for  $t_0 \leq n < t_1$  where

 $t_0$  is the beginning of a trial and  $t_1$  is the end of a trial, representative of MOC activity level, was extracted as a feature (abbreviated as "MOC - HT" in the subsequent chapters).

#### Wavelet Decomposition Transform

To examine frequency-specific fast MOC efferent activity, a 3-level WPT with second order coiflets was performed on individual TEOAEs across the data set. This approach decomposed the data set into 8 frequency sub-bands. The direct computation of CS of TEOAEs and absolute values of Hilbert transform were then used in each sub-band for feature extraction, each yielding an 8-dimensional feature set (abbreviated as "MOC – WPT, CS" and "MOC – WPT, HT" in the subsequent chapters). An exhaustive approach was used to search for the most discriminatory feature set of up to 4 dimensions.

#### 3.4.3 Classification and Validation

In the detection of selective auditory attention, this study was set up with trials of two conditions (i.e., non-attentive and attentive). A two-class classification problem was formed, where seven features were defined. Assuming that the values of the individual features were normal distributed , features were evaluated using linear discriminant analysis with 100 iterations of 5-fold cross validation. Both participant-specific and participant-independent classifiers were

tested with Matlab software, where participant-specific classifier searched for the most discriminatory feature subset based on individual participants' data, and participant-independent classifier searched for the most discriminatory feature subset based on the participant population's data.

The accuracies were compared against chance level via a binomial test (i.e., probability of success = 50%, number of trials = 60; let X denote the number of successfully classified trials, P[X>=30] = 55.12%).

# Chapter 4

# 4 Results and Discussion

# 4.1 Results

In the initial search for a suitable feature for the detection algorithm, 7 candidate features were tested and compared in terms of detection accuracies. Validation was performed with a participant-independent classifier. Best feature subsets were obtained via exhaustive search. Table 1 lists the classification results for the candidate features. Exhaustive feature selection was applied to the multi-dimensional candidate feature sets, namely "OHC - WPT", "MOC - WPT, CS", and "MOC - WPT, HT". Features representing OHC activity performed at near random chance. And most features representing MOC efferent activity performed at higher than random chance.

As the level of attentiveness possibly has an effect on the performance of the auditory detection algorithm, we required a method to remove the attentive trials where the participants were "least attentive" to the tone bursts. To this end, we analyzed the participants' reported tone burst counts. The participants' reported count on the number of tone bursts in each trial was compared with the number of tone bursts actually presented to them during the trial. The delta between the reported and actual counts was calculated. The distribution of tone burst count deltas is presented in Figure 11.

	e				
				Acc	uracy
Feature Genre	Number of Features in Feature Set	Number of Dimensions Considered	Best Feature Subset	Mean	Standard Deviation
OHC -RMS	1	1	N/A	53.05%	4.29%
OHC - time window	5	1	{1}	53.67%	4.90%
	8	1	{3}	54.76%	6.98%
OHC - WPT	8	2	{1,5}	55.65%	7.05%
	8	3	{1,5,6}	56.21%	6.21%
	8	4	{1,2,5,6}	55.16%	6.51%
MOC - CS	1	1	N/A	54.48%	8.55%
MOC – HT	1	1	N/A	62.49%	11.79%
	8	1	{1}	56.92%	12.33%
	8	2	{1,4}	57.42%	13.15%
MOC - WPT, CS	8	3	{2,7,8}	58.24%	13.00%
	8	4	{2,4,7,8}	58.36%	12.23%
MOC - WPT, HT	8	1	{1}	60.43%	11.30%
	8	2	{1,3}	62.41%	11.29%
	8	3	{1,3,5}	63.69%	12.79%
	8	4	{1.2.5.7}	64.87%	12.69%

Table 1: Performance results for the selected feature subsets. Shaded rows are the results of the best feature subset for a feature genre.

The accuracy of the participant's tone burst counts was used as an auditory attention metric. Attentive condition trials were sorted in descending order of tone burst count accuracy. Trials with a tone burst count delta of 8 along with their preceding non-attentive trials were dropped. The performance of the two best features was then re-evaluated. This procedure of removing trials was repeated for tone burst count deltas from 7 down to 1, in unit decrements. At each iteration, an increasing number of trials were removed. The classification results with each reduced set of trials are summarized in Tables 2 and 3. Results showed a small, however, insignificant increase in the performance of the detection algorithm using the feature "MOC – HT". And the performance of the detection algorithm using the feature "MOC – WPT, HT" did not improve post-removal of the "least attentive" trials.



Figure 11: Histogram of deltas between reported and actual counts of tone bursts (mean=-1.2, standard deviation=3.77).

From the initial analysis, the feature "MOC – WPT, HT" demonstrated the highest populationwide classification accuracy. To further investigate this feature, the TEOAE data were examined for each participant, searching for the best feature subset with a participant-specific classifier (Figure 12). The overall classification accuracy with a participant-specific classifier increased to  $70.17\pm12.54\%$ .

	Accuracy		Sensitivity		Specificity	
% Trials Removed	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
64.1	65.16%	11.44%	75.17%	13.55%	55.15%	16.33%
49.49	64.48%	12.22%	74.15%	13.49%	54.81%	15.21%
33.85	63.51%	11.92%	73.51%	13.85%	54.01%	13.24%
22.36	63.21%	10.73%	74.05%	12.96%	52.26%	13.26%
17.69	62.85%	10.22%	73.13%	12.04%	51.70%	13.65%
11.03	62.43%	10.34%	73.39%	12.38%	51.05%	13.65%
6.92	62.65%	10.28%	74.01%	12.16%	51.13%	13.78%
3.85	62.64%	10.83%	73.51%	12.14%	50.95%	14.27%

Table 2: Trials with inaccurate reported tone burst counts were removed from the data set. Classification results were reevaluated using the feature "MOC - HT".

 Table 3: Trials with inaccurate reported tone burst counts were removed from the data set.

 Classification results were reevaluated using the feature "MOC – WPT, HT".

		Accuracy		Sensitivity		Specificity	
	Best						
% Trials	Feature		Standard		Standard		Standard
Removed	Subset	Mean	Deviation	Mean	Deviation	Mean	Deviation
64.1	{1,2,3,7}	63.44%	11.58%	71.03%	13.33%	55.86%	12.56%
49.49	{1,3,5,7}	64.43%	11.74%	71.11%	12.72%	57.75%	12.21%
33.85	{1,5,7,8}	64.33%	13.65%	69.70%	14.20%	58.95%	14.17%
22.36	{1,4,5,7}	66.29%	13.23%	72.58%	13.57%	59.99%	14.55%
17.69	{1,3,5,7}	65.22%	13.00%	72.20%	13.36%	58.24%	13.70%
11.03	{1,3,5,7}	65.44%	13.12%	72.77%	12.89%	58.11%	14.52%
6.92	{1,3,5,7}	65.75%	13.07%	72.99%	12.32%	58.52%	15.01%
3.85	{1,3,5,7}	65.59%	13.18%	72.97%	12.70%	58.21%	15.06%



Figure 12: Performance results for "MOC – WDT, HT" with participant-specific classifier for detection of auditory attention (Accuracy =  $70.17 \pm 12.54\%$ , sensitivity =  $74.00 \pm 14.38\%$ , specificity =  $66.38 \pm 12.52\%$ ).



Figure 13: Frequency of selection for features 1 to 8 in the feature genre "MOC – WPT, HT".



Figure 14: Performance of signal processing algorithm with "MOC – WDT, HT" feature and a participant-independent classifier for detection of auditory attention (Accuracy = 65.92±13.91%, sensitivity = 71.64±14.32%, specificity = 60.19±14.32%).

Figure 13 shows the frequency of selection of the eight features defined using the feature "MOC – WPT, HT", taken from the feature selection process of participant-specific classifiers. Using the four most frequently selected features, three feature subsets were chosen (i.e.:  $\{1,2,6,7\}$ ,  $\{1,3,6,7\}$ ,  $\{1,5,6,7\}$ ) to test the performance of a participant-independent (participant-independent) classifier (Figure 14).

### 4.2 Discussion

In the initial analysis, classification accuracies obtained with features relating to OHC activity were at around random chance (55.12%). These methods failed to detect auditory attention in the data collected from the current study. Classification accuracies from the methods involving fast MOC efferent activity detected auditory attention up to 9.75% above random chance.

An initial concern with the current data set was the issue of motion artifact. During the nonattentive periods, the TEOAE probe wire may have moved against the body as a result of participant motion, thereby introducing low frequency noise into the measurement. This phenomenon may have introduced a negative correlation between "attentiveness" and low frequency noise in TEOAEs. If motion artifact played a role in the detection accuracy of the current algorithm, performance was then expected to be better than random chance across the candidate features. By examining the performance results of the detection algorithms which used OHC activity in feature extraction, these results showed detection accuracies at approximately random chance. Motion artifact, thus, would not have contributed in any appreciable manner to the reported detection performance.

Increases in classification accuracy were observed in feature extraction that used fast MOC efferent activity (Table 1). The feature genre "MOC – WPT, HT" yielded an improvement in classification accuracy of 4.44% when dimensionality increased from 1 to 4 features. The feature "MOC – WPT, CS" yielded an improvement in classification accuracy of 1.44% when dimensionality increased from 1 to 4 features. These findings suggest that there may exist frequency-specific information relating to auditory attention in the fast MOC efferent activity. Although the performance improvement was not significant in the present study, implementation of an participant-specific classifier could further improve the results.

The level of the participant attentiveness to the auditory task was suspected as a possible factor in the quality of the system's performance. The accuracies of the participant's counts of tone bursts served as an objective measure of the participants' attention level. There was a small, however, insignificant increase in the classification accuracy, when the trials with inaccurate reported tone burst counts were removed from the data analysis. Attentiveness and classification accuracy did not have significant correlation. We speculate that attention-related auditory neural activity partially projected on the biomechanical activity in the cochlea via the OCB. Auditory attention manifested as TEOAEs then provided only limited information.

In the current research study, the participants were instructed to listen for and count tone bursts of 1 kHz in pitch during attentive periods. Hypothetically, the focus of auditory attention to 1 kHz tone bursts maps to MOC efferent activity that modulates OHC activity at the 1 kHz location of the cochlea. For performance results with the feature "MOC – WPT, HT", the most frequently selected feature with an participant-specific classifier corresponded to a frequency sub-band between 0 and 750 Hz. This was contrary to [33]. However, increasing the feature set dimensionality, where additional features came from higher frequency sub-bands, improved

classification accuracy. This suggested that auditory attention at a specific pitch frequency possibly enabled mapping to a frequency profile in MOC efferent activity. This finding encourages future studies using tone bursts at two or more frequencies as choices for selective auditory attention.

A system with a participant-specific classifier is often expected to perform at a higher accuracy than a system with a participant-independent classifier. The use of a participant-specific classifier is justified for a TEOAE-based access technology, due to its intersubject variation nature of the physiological signal. In particular, TEOAE as a potential biometrics [19] may imply the need for a signal processing algorithm that is tailored to the user for detection of auditory attention, to account for the "unique signature" of the individual.

# Chapter 5

# 5 Limitations

While the current design and detection algorithm was a successful initial step in detecting selective auditory attention, there are many opportunities for future improvement. Many factors may affect the performance of selective auditory attention detection. This section identifies some potential system and user factors.

# 5.1 System Factors

System factors that may impact detection, include the sound pressure level of the elicitor of TEOAEs [38, 39], time window analysis of TEOAEs [40, 41], the effect of prolonged acoustic stimulation on both ears, and interference due to slow MOC and LOC effects.

In the design of CAS, tone burst frequency, SNR levels, contralateral noise bandwidth and SPLs [42], time period for alternating SPLs of contralateral noise, and the use of auditory cues can also affect performance.

# 5.2 User Factors

Factors relating to the user include age, ear asymmetry, music training, smoking habit, and middle ear function.

Age: CS of EOAEs increases throughout infancy and reaches a plateau at around age three. It begins to decline at around age twenty. By middle age, CS of EOAEs is almost absent (Figure 13) [43]. These findings suggest that an access pathway based on TEOAEs is ideal for individuals between the ages of three and twenty.

Ear asymmetry: Previous studies have also found higher CS of TEOAEs in the right ear than in the left [44, 45, 32]. The right ear enables better measurement of small changes in the suppression and is thus preferred in experiments involving auditory attention.



Figure 15: The rise and decline of CS of EOAE as a function of age (Source [43])

Musicians/non-musicians: Musicians have greater CS of TEOAEs in both ears than nonmusicians [46, 47], suggesting that musicians may be better candidates than non-musicians in the use of TEOAE access pathway.

Smokers/non-smokers: Non-smokers have greater CS of TEOAEs than smokers [48], suggesting that non-smokers may be better candidates.

Middle ear functions: TEOAEs depend on the conduction of sound through the middle ear to convert and amplify cochlear hydrodynamic waves into acoustic vibrations outside the tympanic membrane. Normal middle ear function is required.

### Chapter 6

# 6 Conclusion

Based on the data collected and analyzed within this thesis, the following conclusions can be made.

• The visual task in the current experiment does not affect TEOAEs. The lack of a visual attention effect on TEOAEs, using the current visual task, is in agreement with [31]. This is encouraging for access pathway research using TEOAEs, as visual tasks of low complexity may be integrated into future experiments. This finding supports the practical use of TEOAE in a body-machine interface. A more detailed experiment with a larger sample size, however, needs to be conducted to confirm this finding.

• Selective auditory attention is detectable with an overall accuracy of 70.17±12.54% and bit rate of 2.44±0.30 bits per minute, when participant-specific features are selected from among WPT and HT candidate features. Past research studies also found significant differences in TEOAE analysis between a non-attentive and an attentive auditory condition using at least two separate TEOAE recordings. The current study used a design that enabled single trial detection without imposing a constraint on the detection time interval. This finding is a crucial step in advancing body-machine interface design using TEOAEs.

• Improvement of tone burst count accuracy has a tendency to increase performance, however, not at a significant level. Auditory attention manifested as TEOAEs may not have provided sufficient information, possibly due to attention-related auditory neural activity partially projected on the biomechanical activity in the cochlea via the OCB. This finding suggests that auditory attention is required, however, attentiveness is not important in the performance of TEOAE-based detection algorithm for auditory attention.

• Frequency specificity of selective auditory attention cannot be fully established with the current design. This finding is contrary to [33]. However, increase in the dimensionality of features using wavelet analysis improved classification accuracy, suggesting that auditory

attention to sound can be profiled in the time-frequency plane. Future research may enhance the experimental design to explore frequency-specific detection and to expand upon the body-machine interface design (i.e.: multiple switch access).

This thesis exploited the human physiology of medial olivocochlear efferents for deciphering intent, by the design of an auditory task, contralateral acoustic stimulus, and the use of TEOAE technology. This thesis demonstrated the feasibility of TEOAE as an alternative access pathway. With the current experimental design, the proposed detection algorithm achieved an overall accuracy at an acceptable level for binary communication. These findings provide the foundation for further development of algorithms for the detection of auditory attention in the cochlear responses of individuals with severe disabilities.

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# Appendix A - Vivosonic Integrity V500 System with TEOAE Modality

#### **General Description**

in



Figure 16: TEOAE probe (Source – Vivosonic Integrity User's Manual) The Vivosonic Integrity V500 System (Figure 17) is a Class 2 device the Health Canada medical device list. It is equipped with data acquisition for auditory electro physiology with four test modalities: Auditory Brainstem Response (ABR), Electrocochleography (ECochG), Transient Evoked Otoacoustic Emissions (TEOAE), and Distortion Product Otoacoustic Emissions (DPOAE). Holland Bloorview PRISM Lab purchased the instrumentation with only the TEOAE option.

The Vivosonic Integrity TEOAE instrumentation consists of a wireless signal acquisition device called Vivolink and a personal computer with Vivosonic software for the reception and logging of TEOAE waveforms. An TEOAE ear probe that embedded a speaker and a microphone is wired to the Vivolink device. The TEOAE ear

probe (Figure 16) must be used with a disposable rubber tip (Figure 18) and it must occlude the external ear canal to prevent escape of TEOAE energy during signal acquisition. The Vivolink TEOAE ear probe delivers click stimuli to the ear and records sound waves in a time window following each click stimulus. Data are transmitted to the Vivosonic software for signal processing, analysis, and logging on the notebook computer via Bluetooth communication.



Figure 17: Vivosonic Integrity V500 System (Source – Vivosonic Integrity User's Manual)



Figure 18: Disposable OAE ear tips (Source – Vivosonic Integrity User's Manual)

### **Instrumentation Parameters**

The Vivosonic instrumentation was used with the adjustable parameters shown in **Error! Reference source not found.** It recorded TEOAE responses with a fixed sampling rate of 38400 samples per second. Table 4: TEOAE parameters for this thesis.

Click Stimulation Mode	Non-Linear
Click Duration	80 microseconds
Click Interval	21.12 microseconds
Click Level	80 dB peSPL
Recording Window	2.8 to 12 milliseconds
High Pass Filter Cutoff Frequency	750 Hz
Low Pass Filter Cutoff Frequency	6000 Hz
Artefact Rejection Threshold	Disabled

#### **Data Logging**

A temporary buffer stores 24 consecutive TEOAE responses. TEOAEs that exceed the artifact rejection threshold (default at 55 dB SPL) are discarded. When the buffer is filled, alternate responses are summed, averaged, and logged in a file in Waveforms A and B (i.e., odd-numbered buffer samples are recorded as an averaged response in Waveform A, and even-numbered buffer samples in Waveform B). Note that the artefact rejection threshold is disabled to temporally aligned TEOAE data to the trials of the experiment.

# Appendix B – Investigating the Effect of Visual Attention on TEOAEs

Two sessions of three TEOAE recordings were performed under similar experimental design and protocol as the research study of this thesis. Please refer to Chapter 3 for details. A simple visual task was used and possible visual attention effect on TEOAEs was the purpose of this investigation.

# B.1 Method

#### **B.1.1 Acoustic and Visual Stimuli**

A CAS was designed and applied to the contralateral ear to activate the MOC efferent and enable observations of the CS of TEOAEs. The CAS was produced by Matlab and delivered to the ear with an earphone of frequency range between 20 Hz and 20 kHz. It consisted of a white broadband noise (20 to 10000Hz) alternating between 55 and 70 dB SPL at a period of 4 seconds.

A Matlab GUI was designed to show a visual "probe" symbol with a probability of 75% for one per second, on an LCD in front of the participant.

#### **B.1.2 TEOAE Instrumentation**

TEOAEs were acquired with the Vivosonic Integrity V500 System (Appendix A) from the ipsilateral ear for the detection of visual attention. Non-linear click stimuli of 80 dB peSPL to the ear at 80 microseconds click-1 and 47.35 clicks second-1 (i.e.: sweep-to-sweep time 21.12 milliseconds). TEOAEs were recorded at a time window between 2.8 and 12 milliseconds following each click stimulus. Artifact rejection threshold was disabled to temporally aligned TEOAE data to the trials of the experiment. Industrial sound ear muffs with reduction of 30 dB SPL were used to minimize noise contamination of TEOAEs.

#### **B.1.3 Experimental Protocol**

The individual was instructed to count the occurrence of the symbol during visual attention periods, with each period lasting 25 seconds. In each session, 10 trials of non-attentive condition and 10 trials of attentive condition were interleaved for each recording, repeated three times with five minutes of rest between recordings.



Figure 19: The box plots showed the distributions of feature "OHC - RMS" extracted from 30 trials of non-attentive no-task period and 30 trials of attentive visual task period for Session # 1 (left panel) and Session #2 (right panel).

# B.2 Data Analysis

In the data analysis of test for the effect of visual attention on OHC and MOC activity, two features "OHC – RMS" and "MOC – HT" (please refer

to Sections 3.4) were extracted from 30 trials of non-attentive condition and 30 trials of attentive condition for each participant. Figure 19 showed the distribution of feature "OHC -RMS" for the two visual attention

conditions of the two sessions. Figure 20 showed the distribution of feature "MOC - HT" for the two visual attention conditions of the two sessions. No difference was found in feature "OHC - RMS" (p = 0.40, p = 0.27) or feature "MOC - HT" (p = 0.37, p = 0.35) for both sessions.



As expected, no significant differences are observed in the TEOAE analysis between a no-task condition and an attentive visual task

condition. The visual task in the current experimental design did not affect TEOAEs. The lack of effect of visual attention in TEOAEs, using the

Figure 20: The box plots showed the distributions of feature "MOC - HT" extracted from 30 trials of non-attentive no-task period and 30 trials of attentive visual task period for Session # 1 (left panel) and Session #2 (right panel). current visual task, was in agreement with [31]. It was encouraging for access pathway research using TEOAEs, as visual tasks of low complexity could be integrated into the research study and future experiments without causing interference. It helped advocating the practical use of TEOAE in a body-machine interface design. In future studies, however, experiments for TEOAE-based access pathway research involving visual tasks need to be designed with caution. Further studies of visual attention in the development of TEOAE-based access pathway are necessary, as high variability of results were observed in [34] and the relation of the visual attention effect on TEOAEs for individuals without spontaneous OAEs [35].