EFFECTS OF HEARING AID PROCESSING ON CORTICAL AUDITORY EVOKED POTENTIALS IN NORMAL HEARING INDIVIDUALS

by

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Abstract

Cortical auditory evoked potentials (CAEPs) are currently being investigated as a tool for validation in hearing aid fittings. There is some conflicting evidence regarding the usefulness of CAEPs in this capacity. CAEPs are influenced by stimulus parameters and hearing aids can change these parameters in an unpredictable manner. The purpose of this study was to investigate the effect of rise time after hearing aid processing on the CAEP of 23 normal hearing participants. Two different duration stimuli (60 ms and 120 ms) were processed by three different hearing aids and the output of each hearing aid was recorded. The stimulus parameters were measured for each condition and the stimuli were presented to each participant through an insert earphone. Two blocks of stimuli were used (1) Raw (varied SNR and intensity) and (2) Equalized/Filtered (equalized SNR and intensity). The electroencephalography (EEG) was recorded and the P1-N1-P2 amplitudes and latencies were measured for each condition. A three-factor ANOVA was conducted to observe the effects of (1) rise time, (2) duration, and (3) SNR. A main effect of rise time was observed on the N1-P2 amplitude. This result indicated that hearing aid processing can increase the rise time enough to elicit a decrease in the N1-P2 amplitude. No effects were observed on amplitudes or latencies of the N1-P2 with the alternative stimulus parameters (SNR and duration). Prior to using CAEPs clinically for validation of hearing aid fittings, normative standards should be established. This ensures that differences in the N1-P2 amplitudes are due specifically to audibility and not to the altered stimulus parameter (i.e., after hearing aid processing). Further research should also be conducted on individuals with hearing loss to see if the effects observed in this study would be present with this population. In addition, comparisons of behavioural and CAEP methods of validation would be helpful in determining the validity and reliability of using these methods clinically.
Lay Summary

When prescribing and fitting hearing aids it is important for hearing health professionals to receive reliable information regarding the benefits and limitations experienced by the patient. However, some individuals cannot provide reliable and effective feedback to clinicians (i.e., children, or adults with dementia). In these cases, methods that do not require conscious report of their experience with hearing aids would be beneficial.

Researchers have suggested the use of brain waves (through electroencephalography) to measure the effectiveness of hearing aids for an individual. These particular brain waves are elicited to sound without the conscious effort of the listener. The different characteristics of a sound can affect the brain’s response and hearing aids can alter these characteristics in unpredictable ways.

This study investigated how hearing aids changed three different sound characteristics and how these changes affected the brain wave response in normal hearing individuals. The results demonstrated that the changes that occurred due to hearing aid processing affect the brain’s response which indicates that these measures are not currently ready for clinical use.
Preface

This dissertation is an original product of its author Kelsey Meagher and thesis supervisors Anthony Herdman, Lorienne Jenstad and Anna Van Maanen. All work presented within this document was conducted within the Amplification Research Lab and BRANE Lab at the University of British Columbia. All methods used for this study were reviewed and approved by the Behavioural Research Ethics Board of the University of British Columbia under certificate number #H14-00441.
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<td>AEP</td>
<td>Auditory evoked potential</td>
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<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
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<td>CAEP</td>
<td>Cortical auditory evoked potential</td>
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<tr>
<td>dB</td>
<td>Decibels</td>
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<tr>
<td>DSL.V5</td>
<td>Desired Sensation Level - Version 5.</td>
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<tr>
<td>EEG</td>
<td>Electroencephalography</td>
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<tr>
<td>ERP</td>
<td>Event-related potential</td>
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<tr>
<td>HA</td>
<td>Hearing aid</td>
</tr>
<tr>
<td>KEMAR</td>
<td>Knowles Electronics Manikin for Acoustic Research</td>
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<tr>
<td>ms</td>
<td>Milliseconds</td>
</tr>
<tr>
<td>NAL-NL1</td>
<td>National Acoustics Laboratory – Non-linear 1</td>
</tr>
<tr>
<td>NAL-NL2</td>
<td>National Acoustics Laboratory – Non-linear 2</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
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<td>SPL</td>
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Dedication

To my wonderful and beloved family – each of you have influenced and shaped the person I am today. I owe my achievements to you and your continuous love, support and inspiration.
Chapter 1: Introduction

According to the World Health Organization (2017), three hundred and sixty million people are affected by hearing loss across the globe. Some common interventions that allow deaf and hard-of-hearing individuals access to the sounds of speech are amplification (i.e., hearing aids), and cochlear implants. In addition to these interventions, many people with hearing loss benefit from speech therapy and aural rehabilitation to learn and fully develop spoken language. Furthermore, a critical period has been investigated where children must have access to spoken language in order to fully develop and learn spoken languages (Yoshinaga-Itano et al., 1998 & 2000). Therefore, early identification of hearing loss and early intervention (e.g., amplification) is essential for families who choose spoken language as their primary means of communication. Research shows that children with hearing loss, who are identified and treated by 6 months of age, perform better on receptive and expressive language outcomes than those identified and treated after 6 months of age (Meinzen-Derr, Wiley, & Choo, 2011; Pimberton & Kennedy, 2012; Yoshinaga-Itano et al., 1998). To ensure that children with hearing loss are identified as early as possible, government systems are responsible for implementing early hearing detection and intervention programs. The Canadian early hearing programs, and other international hearing programs, use a standard where infants receive a hearing screening by 1 month of age, hearing loss is identified by 3 months, and intervention (e.g., amplification, cochlear implant, communication services) is provided by 6 months of age (Joint Hearing Committee on Infant Hearing, 2007; Speech and Audiology Canada, 2017; Provincial Health Authority, 2009). Therefore, intervention programs that include amplification or cochlear implantation are vital in allowing children to receive early input to the auditory system ensuring that they fall within the
normal range of speech and language development. As such, it is crucial that these assistive devices are properly programmed to ensure that speech is audible for these children.

With both adults and children, hearing health professionals are trained to use verification methods when fitting amplification to ensure that sounds are audible and comfortable for clients. The verification process includes the use of prescriptions (e.g., DSL.V5, NAL-NL1, NAL-NL2, etc), which generate target decibel levels for the hearing aid at each frequency by considering the severity and type of hearing loss. These prescriptions have been extensively researched to ensure that appropriate gain is provided across the frequency range for a variety of hearing losses. Each prescription uses a unique philosophy that aims to provide optimal benefit by ensuring intelligibility, comfort, and audibility (Ching et al, 2013; Polonenko et al., 2010; Keidser, Dillon, Carter, & O’Brien, 2012). These prescriptions provide hearing health professionals with a preliminary guide from which they can adjust the frequency response of the hearing aids based on patient report. Recently, research revealed the importance of assessing outcomes of hearing aid fittings through subjective and objective validation methods (Valente et al., 2006; Mendel, 2007; Cox, Alexander, & Beyer, 2003; Jorgensen, 2016; Hyde, 2002). Subjective validation methods, such as questionnaires, are used to evaluate the effectiveness of amplification in the patient’s daily life (Mendel, 2007) and can assist the hearing health professionals in future adjustments to ensure that the patient is receiving sufficient benefit from amplification. The Abbreviated Profile of Hearing Aid Benefit (APHAB) (Cox & Alexander, 1995) and Client Oriented Scale of Improvement (COSI) (Dillon, James, & Ginis, 1997) are only two of such validation questionnaires that have been researched and supported in their ability to provide significant information regarding the effectiveness of hearing aids for adults with hearing loss. There is also objective validation through the use of quantitative measures such as the hearing in
noise test (HINT) (Nilsson, Soli, & Sullivan, 1994) and the QuickSIN (speech in noise) test (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004; Wilson, McArdle, & Smith 2007). These objective tests are used pre- and post-hearing aid fitting to determine if improvement is observed with the use of hearing aids. This can provide the hearing health care professional with information regarding the benefits and limitations of the technology. This information assists the clinician in deciding where to proceed with this patient. These types of subjective and objective validations are only effective for persons who can reliably report on their experiences and actively participate in the evaluation. However, some populations, including infants or children, and adults with dementia or expressive language impairments, are unable to accurately and reliably report on their perception and experience with amplification. In addition, they are often unable to participate in objective assessments for validation purposes. In these cases, subjective parent or guardian questionnaires were created to evaluate the perceived benefit of amplification such as the Parent Evaluation of Aural/Oral Performance of Children (PEACH) (Ching, & Hill, 2007) or the Significant Other Assessment of Communication (SOAC) (Sahin, Başar, & Güven, 2012). However, these subjective questionnaires are not able to fully represent and assess what the individual is perceiving or experiencing. Therefore, objective measures that do not require full participation to evaluate the effectiveness of hearing aids for these populations would be preferable.

1.1 Auditory Evoked Potentials

Auditory evoked potentials (AEPs) are objective measures used by audiologists to determine hearing thresholds of individuals unable to participate reliably in behavioral audiometry. AEPs are the electrical potential changes in the auditory system which are generated
in response to auditory stimulation (Picton, 2011). These changes in the electrical potentials can be recorded on the scalp and used as objective measures in the identification of hearing loss and other auditory pathologies (Picton, 2011; Katz et al., 2015). There are several classifications of AEPs which are categorized based on their latency (i.e., early-, middle-, and late-latency waves). The latencies of the AEPs are dependent on the corresponding physiology and the duration required for the auditory signal to be transmitted through the auditory system (Picton, 2011; Katz et al., 2015). Some of these classifications include auditory brainstem response, auditory steady-state response, middle-latency response, and cortical auditory evoked potentials (CAEPs). All AEPs regardless of their classification are elicited without the person having to provide conscious effort in the detection of a present stimulus.

All AEPs have benefits and limitations that should be considered prior to their use. Some AEPs are better than others for certain populations. Early latency waves, such as the auditory brainstem responses, are not affected as significantly by maturational effects such as myelination of neurons, which is a critically important factor to consider in the use of objective measures for infants. However, the recording of the auditory brainstem response requires the patient to be asleep or sedated (Picton, 2011) which is not preferred when testing adult populations. Middle latency waves are still being researched in their efficacy in the audiological assessment (Picton et al., 1998; Hatzopoulos, Petrarelli, Śliwa, Jędrzejczak, Kocharanek, & Skarżyński, 2012; Casey, 2012; Tomlin, Rance, Graydon, & Tsialios, 2006). Therefore, their usefulness and efficacy are still being investigated for clinical use for all populations. Late latency waves such as the CAEP, can only be recorded when patients are awake and are significantly affected by maturation of the auditory system. Therefore, this method of testing is unreliable when testing infants. Adults with fully developed and myelinated auditory systems will elicit a clear P1-N1-P2 complex, whereas
infants and young children sometimes elicit P1-N1 and these responses are not always present (Seewald & Tharpe, 2017; Sharma, Dorman, & Spahr, 2002; Ponton, Eggermont, Kwong, & Don, 2000). This makes it difficult to use CAEPs reliably for children, however, CAEPs are the preferred method of testing for adult populations.

The majority of these AEPs have been proposed as effective methods for hearing aid validation. More specifically, the auditory brainstem responses (e.g., Kileny, 1982; Anderson, Parbery-Clark, White-Schwoch, & Kraus, 2013; Hecox, 1983), auditory steady-state responses (e.g., Picton et al., 1998; Shemesh, Attias, Magdoub, & Nageris, 2012; Stroebel, Swanepoel, Groenewald, 2007), middle latency responses (e.g., Kurnaz, Satar, & Yetiser, 2009) and CAEPs (e.g., Korczak, Kurtzberg, & Stapells, 2005) have been researched for efficacy in evaluating hearing aid fittings. However, for the purpose of this study, the focus of the following sections will be on the CAEP and the research surrounding the efficacy of their use in the validation of hearing aid fittings.

1.2 Influence of Stimulus Parameters on the CAEP

Prior to discussing the efficacy of the use of CAEPs for validation of hearing aid fittings, it is important to understand the effect of stimulus parameters on the CAEP. CAEPs are inherently influenced by many different stimulus parameters including signal-to-noise ratio (SNR), duration, stimulation rate, rise time, and intensity.

1.2.1 SNR

The CAEP is influenced by the SNR of the stimulus (Billings et al., 2011; Billings et al., 2009; Billings et al., 2007; Billings & Grush, 2016; Billings, Penman, McMillian, & Ellis, 2015).
More specifically, a decreased SNR causes an increased latency and decreased amplitude of the CAEP P1-N1-P2 complex (Billings et al., 2009; Billings & Grush, 2016). Although low SNRs have been found to reduce the N1 amplitude, low levels of noise have been proven to increase the N1-P2 amplitude when compared to quiet conditions (Alain, Quan, Mcdonald, & Van Roon, 2009; Paberty-Clark, Marmel, Bair, & Kraus, 2011). Researchers have suggested that this could be due to the phenomenon referred to as stochastic resonance where noise causes an improvement in a system’s efficiency (Picton, 2011; Stufflebeam, Poeppel, Roberts, 2000; Ries, 2007). However, researchers have also indicated that binaural stimulation with a fast stimulation rate is required to elicit this increase in N1-P2 amplitude in low noise conditions (Papesh, Billings, & Baltzell, 2015). In addition, the P2-N2 amplitudes are only affected when SNR levels are low (i.e., SNR value of 0-10 dB) (Whiting, Martin, & Stapells, 1998; Billings et al., 2009).

1.2.2 Duration

Research shows that with an increase in duration the N1-P2 amplitude gets larger and the latency decreases (Alain, Woods, & Covarrubias, 1997; Joutsiniemi, Hari, & Vilkman, 1989). Other research also found that the P1-N1-P2 complexes do not change after 50 ms duration (Picton, 2011). If rise time is fast (3 to 5 ms), an increase in duration can cause the P1-N1-P2 amplitudes to increase to a duration of 70 ms, and at longer durations the CAEP response amplitude decreases (Picton, 2011). For longer rise times, it is likely that the N1-P2 is responding to both the duration and rise time of the stimuli during the first 50 ms (Picton, 2011). Picton (2011) also noted that the optimal duration for a tone is one that has a rise and fall time of between 10 and 20 ms and a plateau time of 30 ms, which is an overall duration of approximately 50 ms.
1.2.3 Stimulus Onset Asynchrony

Stimulus onset asynchrony refers to the length of time between stimulus presentations (Picton, 2011). As stimulus onset asynchrony increases the amplitude of the P1-N1-P2 response also increases (Davis, Mast, Yoshie & Zerlin, 1969; Milner, 1969; Nelson & Lassman, 1968). However, correlations between stimulus onset asynchrony and intensity have also been found (Picton et al., 1970). Stimuli with lower intensities are not as affected by changes in stimulus onset asynchrony as stimuli with higher intensities. Picton et al. (1970) found that N1-P2 amplitude differences tend to saturate at high intensities (> 60 dB HL) when the stimuli are presented at more rapid rates (stimulus onset asynchrony of < 3 s). However, when presented at slower rates (stimulus onset asynchrony of > 3 s) the N1-P2 amplitudes continue to increase at high intensity levels (> 60 dB HL). Overall, the effect of the stimulus onset asynchrony is larger for louder stimuli (for review see Picton, 2011).

1.2.4 Absolute Intensity

Intensity can affect the P1-N1-P2 complex of the CAEP (Onishi & Davis, 1968; Picton, 2011, chapter 11). More specifically, research showed that with increased intensity, the N1-P2 amplitudes increase and latencies decrease (Picton, 2011; Onishi & Davis, 1968; Rapin, Schimmel, Tourk, Krasnegor, & Pollak, 1966). However, absolute intensity has a nonlinear effect on the amplitude of the N1-P2, where intensity over 50 dB SPL with a stimulus interval of 1.5 ms would not cause a significant increase in the N1-P2 amplitude or decrease in the N1-P2 latencies (Picton, Goodman, & Bryce, 1970). Another study also observed the interaction and effect of SNR and intensity (Billings et al., 2009). They found that intensity did not have
significant effects on the N1-P2 amplitude and latencies, rather SNR was the significant influencer on the N1-P2 amplitude and latency (Billings et al., 2009).

1.2.5 Rise Time

Rise time can also influence the P1-N1-P2 complex (Kodera et al., 1979; Onishi & Davis, 1968). Onishi and Davis (1968) found that rise times less than 30 ms does not significantly affect the N1-P2 amplitude; however, when rise times exceed 30 ms the N1-P2 amplitude decreases. In addition, they found that as rise time increases the N1-P2 latency also increases (Onishi & Davis, 1968). Kodera (1979) found that the P1-N1 amplitude decreased with the increase in rise time when observing the effects of stimuli with 5, 10, and 20 ms rise times, but the N1-P2 amplitude change was not significant.

1.3 Hearing Aids

As discussed previously, CAEPs have been proposed as a possible tool in the validation of hearing aid fittings for individuals who are unable to reliably report on their experience. Currently, commercial CAEP systems are being marketed to clinicians as a reliable method of validation of hearing aid fitting. However, clinicians must consider the unreliable changes that occur with hearing aid processing prior to implementing these systems in the clinic.

 Interestingly, much of the research on aided cortical potentials is inconsistent in showing increased cortical responses after amplification. Some studies show expected increases in amplitudes and decrease in latencies of the CAEP (e.g., Chang, Dillon, Carter, Van Dun, & Young, 2012; Durante et al., 2014; Korczak, Kurtzberg, & Stapells, 2005; Kuruvilla-Mathew, Purdy, & Welch, 2015) while others did not find this expected outcome (e.g., Billings, Tremblay,
Souza & Binns, 2007; Billings, Tremblay & Miller, 2011; Billings, Papesh, Penman, Batzell & Gallun, 2012; Marynewich, Jenstad, & Stapells, 2012; Tremblay, Billings, Friesen, & Souza, 2006). These inconsistencies could be partially owed to the unpredictable changes that occur due to hearing aid processing (Chasin & Russo, 2004; Dillon, 2012; Souza, 2002; Souza, Jenstad, & Boïke, 2006; Jenstad, Maryrewich, Stapells, 2012; Huen, 2016). In addition, these inconsistencies could also be attributed to differences in participant populations (e.g., normal hearing vs. hearing loss).

There are several factors that affect the overall output of a hearing aid such as receiver strength/frequency response of the receiver, compression algorithms, and properties of the external portion of the hearing aid including ear hooks, dampers, ear-mold tubing, and ear-mold characteristics (Dillon, 2012). These factors influence the signal output of the hearing aid by altering stimulus parameters including the SNR (Dillon, 2012; Souza et al., 2006), duration (Souza, 2002), rise time (Souza, 2002; Dreschler, 1988), and absolute intensity (Souza, 2002) relative to the input signal.

Recently, a comprehensive analysis was completed that quantified the effects of three different hearing aid models on several auditory evoked potential stimuli (Huen, 2016). Huen (2016) found that hearing aid processing caused significant variability in many of the acoustic parameters of these different stimuli. Her study observed an influence of hearing aid processing on the stimulus parameters of the input signals, and one of the most significant changes observed through her study was the effect on the rise time of the CAEP tone-bursts (Huen, 2016). More specifically, Huen (2016) found that in some conditions hearing aid processing caused an elongation of rise time when compared to the respective input stimulus.
As discussed in Section 1.2, rise time has a significant effect on the N1-P2 amplitude of the cortical potential when it exceeds 30 ms (Picton, 2011; Kodera et al., 1979; Onishi & Davis, 1968). A recent study on the effect of rise time on the aided cortical potential concluded that the changes in rise time observed through hearing aid processing did not affect the amplitude and latency of the P1-N1-P2 complex for normal hearing listeners (Easwar, Glista, Purcell, & Scollie, 2012). However, it is important to note that their study used only one hearing aid which did not create a change in rise time that exceeded 30 ms, which was suggested by Onishi & Davis (1968) as the criterion for influencing a decrease in N1-P2 amplitudes and increase in latencies. Currently, no research has been conducted comparing the aided rise time from more than one hearing aid with rise times exceeding 30 ms.

1.4 Physiological Considerations

Hearing loss occurs with changes to the physiology of the hearing system. With these changes in the physiological structures, the response of the auditory system to sound is also affected (for example, threshold elevation, decreased frequency specificity, and recruitment of neural networks). One study observed the effect of signal parameters on the CAEP in both, normal hearing individuals, and individuals with hearing loss (Van Dun, Kania, & Dillon, 2016). They found that in normal hearing individuals, increasing the gain did not significantly affect the N1-P2 amplitudes and latencies of the CAEP. However, the N1-P2 amplitudes did increase for those individuals with hearing loss (Van Dun et al., 2016). This result indicates that the impaired auditory system may not be influenced by changes in these stimulus parameters like that of a normal auditory system.
1.5 Aim of This Study

The purpose of this study is to observe the influence of hearing aid processing on the CAEP of normal hearing individuals without the added influence of hearing loss. This study is designed to specifically investigate the influence of rise time after hearing aid processing on the N1-P2 amplitudes and latencies of the CAEP.
Chapter 2: Methods

2.1 Participants

Twenty-three individuals between the ages of eighteen and thirty years participated in the study. All participants were required to have normal hearing with no reported history of neurological, cognitive, or otological disorders. This study was performed in accordance to the ethical standards and approval provided by the Behavioural Research Ethics Board at the University of British Columbia and each participant provided written informed consent to participate in the study. Recruitment took place at the University of British Columbia through word of mouth, and flyers posted around campus and in the community. Participants also received an honorarium for their time.

2.2 General Study Procedures

2.2.1 Audiometric Assessment

Otoscopy was conducted to ensure that there were no contraindications, including drainage, occluding cerumen, or foreign bodies in the ear canal. Pure-tone hearing thresholds were screened using air conduction through ER-3A insert earphones with an InterAcoustics audiometer. Bilateral air-conducted thresholds were required to be better than 25 dB HL from 250-8000 Hz. The hearing screening and the remainder of the experiment were conducted in a soundproof booth located in the BRANE lab at the University of British Columbia.
2.2.2 Stimuli

All stimuli for this study were taken from the comprehensive analysis on hearing-aid processing effects on AEPs conducted by Huen (2016). Huen (2016) used three different hearing aids from three different manufacturers. All hearing aids were programmed for a mild sloping to moderately-severe hearing loss, and were set and verified to DSL V.5 prescriptive targets using the long-term average speech spectrum at 65 dB SPL (Huen, 2016). Stimuli were created through Audacity® and MATLAB based on stimuli used clinically at WorkSafeBC and previous research studies (Huen, 2016; Billings et al., 2007; Billings et al., 2012; Martin & Boothroyd, 2000). Unaided stimuli were presented through sound field at 45 dB SPL and 65 dB SPL (Huen, 2016) and the output of each hearing aid, as well as an unaided condition, was recorded by a microphone in Knowles Electronic’s Manikin for Acoustic Research’s (KEMAR) left ear (Huen, 2016).

For the purpose of the current study, the unaided stimuli refer to the unprocessed stimuli that were presented through sound field and recorded in the left ear canal of KEMAR in Huen (2016). The aided stimuli will refer to the processed stimuli recorded in the left ear canal of KEMAR with one of the hearing aids in place (Huen, 2016). In addition, Huen (2016) refers to the hearing aids by their manufacturer name; in this study, Phonak, Siemens and Starkey hearing aids will be referred to by HA#1, HA#2 and HA#3 respectively.

Stimuli Selection. Huen (2016) collected data on a wide variety of AEPs including auditory brainstem response, auditory steady-state response, middle latency response, mismatch negativity, acoustic change complex, and slow cortical response stimuli. For the purpose of this study the aided and unaided slow cortical response stimuli were used. The 1000 Hz tone bursts
were selected as the majority of prior work had been conducted using this frequency (Billings et al., 2016; Billings et al., 2011; Billings et al., 2006; Billings et al., 2009; Vijayalakshmi et al., 2012). Huen (2016) recorded 12 conditions for the 1000 Hz slow cortical potentials tone burst (two different compression conditions: linear and wide dynamic range compression; three different rise times: 5 ms, 10 ms, and 20 ms; and two different input intensities: 45 dB SPL and 65 dB SPL). The stimuli for this study were selected by observing the contrast in aided rise times generated within each unaided rise time condition. The contrasts within each rise time condition were then compared to determine which group provided the greatest contrast in rise time while maintaining consistency across other stimulus parameters (i.e., SNR, gain, and duration). All hearing aid processing parameters for the 1000 Hz tone-burst data were crosschecked to determine if all stimulus parameters remained constant across conditions (for review see Huen, 2016). SNR and gain values for the aided conditions were required to be within 3 dB across conditions to prevent the influence of SNR on the CAEP wave forms. In addition, duration, and rise time were considered in the selection process. Past research indicated that with faster rise times (i.e., 3 to 5 ms) duration can have an effect on the CAEP but only up until 70 ms duration (Picton, 2011; Onishi & Davis, 1969; Kodera et al., 1979). In addition, Picton (2011) indicated that 50 ms duration tones were optimal for CAEPs. Therefore, durations below 50 ms were excluded from stimulus selection to ensure that duration of the tone would not affect the CAEP. Furthermore, aided rise times were compared with unaided rise times to determine which stimuli would provide substantial contrast (greatest change vs. least amount of change). In addition, rise times of aided stimuli were required to have at least one condition that was less than 30 ms and one condition was 30 ms or greater. This criterion was selected because rise times between 30-50
ms are expected to cause the N1-P2 amplitude to decline (Alain et al., 1997; Kodera et al., 1979; Onishi & Davis, 1969).

Based on the above criteria, linear recordings with 60 ms and 120 ms durations were selected due to greater consistency of stimulus parameters across conditions when compared to compression recordings. The 60 ms and 120 ms duration stimuli with 20 ms rise times were selected due to the greatest consistency amongst stimuli parameters (i.e., SNR, duration, gain, intensity) and largest contrast in rise time across aided conditions. HA#1 had the greatest increase in rise time, and HA#3 the least amount of change in rise time (< 1 ms) across durations (See table 2.1; Table 2.2; Table 2.3; Table 2.4). Unaided stimuli had significantly higher SNR values when compared to the consistent SNR values of the aided conditions. This change in SNR has been known to affect the N1-P2 amplitude and latency (Billings et al., 2009). Therefore, two blocks of stimuli were used. The first was the unaltered stimuli from Huen (2016) and the second was a filtered block with equalized SNR and intensity.

**Raw Stimuli Block.** This block of stimuli consisted of the raw recordings from Huen (2016). Hereafter, this block of unaltered stimuli will be referred to as the Raw Stimuli. All stimuli parameters are represented in Table 2.1 and Table 2.2 and stimuli envelopes can be observed through figure 2.1 and 2.2. Figure 2.2 shows each stimulus envelope with their corresponding rise time.
<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Relative Amplitude (to unaided)</th>
<th>SNR (dB SPL)</th>
<th>Rise time (ms)</th>
<th>Maximum Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaided</td>
<td>N/A</td>
<td>28</td>
<td>19</td>
<td>50</td>
</tr>
<tr>
<td>HA #1</td>
<td>-13</td>
<td>15</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>HA #2</td>
<td>-11</td>
<td>18</td>
<td>23</td>
<td>13</td>
</tr>
<tr>
<td>HA #3</td>
<td>-8.0</td>
<td>18</td>
<td>20</td>
<td>21</td>
</tr>
</tbody>
</table>

**Table 2.1** Raw Stimuli Parameters – unaltered; measured from the 60 ms duration recordings

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Relative Amplitude (to unaided)</th>
<th>SNR (dB SPL)</th>
<th>Rise time (ms)</th>
<th>Maximum Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaided</td>
<td>N/A</td>
<td>28</td>
<td>19</td>
<td>51</td>
</tr>
<tr>
<td>HA #1</td>
<td>-8</td>
<td>21</td>
<td>51</td>
<td>10</td>
</tr>
<tr>
<td>HA #2</td>
<td>-8.0</td>
<td>18</td>
<td>39</td>
<td>13</td>
</tr>
<tr>
<td>HA #3</td>
<td>-8.0</td>
<td>19</td>
<td>19</td>
<td>21</td>
</tr>
</tbody>
</table>

**Table 2.2** Raw Stimuli Parameters – unaltered; measured from the 120 ms duration recordings

**Figure 2.1** Raw Stimuli Block – stimulus envelope
Figure 2.2 Raw Stimuli – with corresponding rise times (pink dots) for 60 ms and 120 ms duration tone bursts

*Equalized/Filtered Stimuli Block.* In order to eliminate the potential confounding variable of having slight differences in SNR and absolute intensities between hearing aid conditions and the unaided condition, a second block of stimuli was created. This block of stimuli was created by filtering aided recordings between 950 – 1050 Hz to remove baseline noise in all conditions. The overall amplitude of the aided stimuli was then increased to match the amplitude of unaided stimuli. Rise times were then examined to ensure that rise time remained consistent with its corresponding raw stimuli condition. This block of stimuli isolated rise time and eliminated potential confounds surrounding SNR and intensity changes. Hereafter, this group of stimuli will be referred to as the Equalized/Filtered Stimuli. All Equalized/Filtered Stimuli parameters can be observed in Table 2.3 and Table 2.4, and stimulus envelopes can be seen in Figure 2.3 and Figure 2.4. Figure 2.4 shows the stimulus envelopes with their corresponding rise times.
<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Relative Amplitude (to unaided)</th>
<th>SNR (dB SPL)</th>
<th>Rise time (ms)</th>
<th>Maximum Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaided</td>
<td>0</td>
<td>60</td>
<td>19</td>
<td>48</td>
</tr>
<tr>
<td>HA #1</td>
<td>0</td>
<td>60</td>
<td>30</td>
<td>38</td>
</tr>
<tr>
<td>HA #2</td>
<td>0</td>
<td>60</td>
<td>23</td>
<td>43</td>
</tr>
<tr>
<td>HA #3</td>
<td>0</td>
<td>60</td>
<td>20</td>
<td>49</td>
</tr>
</tbody>
</table>

**Table 2.3** Equalized/Filtered Stimuli Parameters – altered 60 ms duration stimuli to account for SNR and Intensity

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Relative Amplitude (to unaided)</th>
<th>SNR (dB SPL)</th>
<th>Rise time (ms)</th>
<th>Maximum Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaided</td>
<td>0</td>
<td>60</td>
<td>19</td>
<td>49</td>
</tr>
<tr>
<td>HA #1</td>
<td>0</td>
<td>60</td>
<td>51</td>
<td>23</td>
</tr>
<tr>
<td>HA #2</td>
<td>0</td>
<td>60</td>
<td>39</td>
<td>30</td>
</tr>
<tr>
<td>HA #3</td>
<td>0</td>
<td>60</td>
<td>19</td>
<td>49</td>
</tr>
</tbody>
</table>

**Table 2.4** Equalized/Filtered Stimuli Parameters – altered 120 ms duration stimuli to account for SNR and Intensity
Figure 2.3 Equalized/Filtered Stimuli Block – stimulus envelope

Figure 2.4 Equalized/Filtered Stimuli – with corresponding rise times (pink dots) for 60 ms and 120 ms duration tone bursts
2.2.3 Stimulus Presentation

Tone bursts were presented in randomized order through ER-3A insert earphones with a stimulus onset asynchrony of 1.5 seconds at 60 dB SPL. The stimulus onset asynchrony refers to the length of time between tone bursts of the stimuli. The baseline noise of the aided recordings was added into the inter-stimulus interval within the Raw Stimuli block recordings to ensure that the stimulus onset asynchrony was 1.5 seconds. Trigger pulses were created and time-locked to the onset of each tone burst in each condition. This allowed the experimenter to observe responses occurring in the CAEP window of 30 to 500 ms. All conditions were presented in the participant’s left ear while a foam ear plug was placed in the participant’s right ear to avoid stimulus cross over to the non-test ear. Each block and conditions of stimuli were presented in randomized order to avoid confounds of participant fatigue. Experimentation was conducted in a soundproof booth and participants were instructed to ignore the stimuli by focusing on a closed-captioned movie of their choice. In addition, participants were asked to limit their head, eye, and body movements during recordings to avoid myogenic interference. Testing was carried out in one three-hour session; however, participants were able to take breaks at any point during the session with forced breaks between blocks to mitigate the effects of participant fatigue on the CAEP (Lavoie, Hine, & Thornton, 2008).

2.2.4 Stimulus Calibration

The output of the left ER-3A insert earphone was calibrated using a Quest Electronics model 1800 sound level meter with a Brue & Kjaer DB0138 2-cc adapter. Calibration was conducted prior to each experimental session with participants. The calibration was conducted using the unaided stimuli for the long and short duration tones in both the Raw and
Equalized/Filtered blocks. The four unaided stimuli conditions were presented through InterAcoustics™ audiometer at 90 dB SPL and adjustments were made to the output of the audiometer if the level measured at the earphone was greater than 91 dB SPL or less than 89 dB SPL.

2.3 Cortical Auditory Evoked Potential Recording

Electroencephalography (EEG) was recorded using a 64-channel BioSemi™ electroencephalography electrode cap. EEG was sampled at a rate of 1024 Hz. Trigger pulses were created by the stimulus software and time-locked to the tone-burst onset for each condition. CAEPs were calculated online by filtering the ongoing EEG between 1-20 Hz, epoching the EEG between -0.5 to 1.0 sec relative tone-burst onset, rejecting epochs with voltages exceeding ± 100 µV (i.e., artefact rejection), separating artefact-free epochs evenly into two buffers, and then averaging the epoch buffers to obtain two event-related potential (ERP) replications. Presence and absence of the P1-N1-P2 wave was determined online by using a custom MATLAB program. Two criteria were set a priori to determine when to stop collecting EEG data for each condition. These criteria were created based on past CAEP data collected by Angel (2016). A CAEP was deemed present if the two replications had a visually repeatable waveform within the 50-300 ms interval with an N1-P2 morphology and the standard-deviation ratio (Picton, 2011) was 1.5 µV with a residual noise level of < 0.08 µV. The standard deviation ratio was calculated as the standard-deviation of the averaged replications between 50-300 ms divided by the standard-deviation of the replications difference waveform between 50-300 ms (Picton, Linden, Hamel & Maru, 1983). The second stopping criterion was for an absent CAEP which had no visually apparent waveform (i.e., no repeatable N1-P2 wave) and a residual noise level of
≤ 0.8 µV (i.e., standard deviation between the replications). If during the recording session, the condition did not meet the criteria for response present or response absent after 200 accepted epochs then the researcher stopped collecting EEG data for that condition.

2.4 CAEP Labeling Procedures

Participants’ recordings were averaged for each condition and then presented to an experienced rater through a custom-coded MATLAB program. The experienced rater selected N1 and P2 peaks based on morphology, and replicability. If the rater judged an absent CAEP (i.e., no definitive N1 or P2 peak), then the rater gave a zero value for both N1 and P2 peaks for that respective averaged waveform. However, this only occurred in one condition for one of the participants. The event-related potentials were then grand averaged for each condition and corresponding N1 and P2 amplitudes and latencies were used for analysis.

2.5 Analysis

Fourteen of twenty-three participants provided complete data sets (for each of the 16 conditions), which were used in the analysis. The nine rejected participant datasets were excluded because of poor SNR (residual noise > .80) in more than one condition. A three-factor repeated-measures analysis of variance (ANOVA) was conducted for the N1 and P2 amplitudes and latencies. The ANOVA main effects were hearing aid rise time (unaided vs. three aided conditions), duration (60 ms vs. 120 ms), and SNR (Raw Stimuli vs. Equalized/Filtered Stimuli). An alpha level of .05 was used to interpret ANOVA results. The null hypothesis was rejected if the p-value was < .05. Tukey’s post-hoc analyses were performed for significant ANOVA results. Post-hoc results were considered significant at an alpha level of .05.
Chapter 3: Results

The grand-averaged ERPs showed typical N1-P2 response waveform morphologies and topographies (Figure 3.1). The N1-P2 peak-to-peak amplitudes appeared to decrease with increasing rise times (moving up the page across hearing aids). A three-factor ANOVA was used to statistically evaluate the effects of rise times, stimulus duration, and SNR on the N1 and P2 amplitudes and latencies. This study found a significant main effect of hearing-aid rise time on the N1-P2 amplitudes, but not on latencies. This study did not find significant main effects for SNR or duration on both, N1-P2 amplitudes and latencies. Furthermore, this study did not find significant interaction effects (i.e., duration x SNR, duration x hearing aid rise time, SNR x hearing aid rise time, and SNR x hearing aid rise time x duration) on the N1-P2 amplitudes and latencies. The ANOVA results are provided in Table 3.1.

**Figure 3.1** Grand averaged event-related potentials for each of the 16 conditions (rise times increase as we move from unaided upward to HA#1 conditions). Grand averaged topographies of N1 (99 ms) and P2 (153 ms) peaks are presented on the right.
<table>
<thead>
<tr>
<th>Source</th>
<th>CAEP feature</th>
<th>Sum Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
<th>F</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hearing Aid Rise Time</td>
<td>N1-P2 Amplitude</td>
<td>82.48</td>
<td>3,195</td>
<td>27.4921</td>
<td>4.36**</td>
<td>0.0053**</td>
</tr>
<tr>
<td></td>
<td>N1 Latency</td>
<td>0.00033</td>
<td>3, 195</td>
<td>0.00011</td>
<td>0.22</td>
<td>0.8813</td>
</tr>
<tr>
<td></td>
<td>P2 Latency</td>
<td>0.00001</td>
<td>3, 195</td>
<td>0</td>
<td>0.01</td>
<td>0.9993</td>
</tr>
<tr>
<td>Duration (60 ms vs. 120 ms)</td>
<td>N1-P2 Amplitude</td>
<td>12.92</td>
<td>1, 195</td>
<td>12.9184</td>
<td>2.05</td>
<td>0.1538</td>
</tr>
<tr>
<td></td>
<td>N1 Latency</td>
<td>0.0002</td>
<td>1, 195</td>
<td>0.0002</td>
<td>0.39</td>
<td>0.5312</td>
</tr>
<tr>
<td></td>
<td>P2 Latency</td>
<td>0.00173</td>
<td>1, 195</td>
<td>0.00173</td>
<td>2.15</td>
<td>0.1441</td>
</tr>
<tr>
<td>Duration x Hearing Aid Rise Time</td>
<td>N1-P2 Amplitude</td>
<td>26.72</td>
<td>3,195</td>
<td>8.9081</td>
<td>1.41</td>
<td>0.2411</td>
</tr>
<tr>
<td></td>
<td>N1 Latency</td>
<td>0.00102</td>
<td>3, 195</td>
<td>0.00034</td>
<td>0.68</td>
<td>0.5676</td>
</tr>
<tr>
<td></td>
<td>P2 Latency</td>
<td>0.00031</td>
<td>3, 195</td>
<td>0.00031</td>
<td>0.39</td>
<td>0.5335</td>
</tr>
<tr>
<td>SNR x Duration Interaction</td>
<td>N1-P2 Amplitude</td>
<td>5.11</td>
<td>1, 195</td>
<td>5.1122</td>
<td>0.81</td>
<td>0.3689</td>
</tr>
<tr>
<td></td>
<td>N1 Latency</td>
<td>0.00029</td>
<td>1, 195</td>
<td>0.00029</td>
<td>0.58</td>
<td>0.4478</td>
</tr>
<tr>
<td></td>
<td>P2 Latency</td>
<td>0.00001</td>
<td>1, 195</td>
<td>0.00001</td>
<td>0.01</td>
<td>0.9372</td>
</tr>
<tr>
<td>SNR x Hearing Aid Rise Time</td>
<td>N1-P2 Amplitude</td>
<td>2.4</td>
<td>3,195</td>
<td>0.7992</td>
<td>0.13</td>
<td>0.9442</td>
</tr>
<tr>
<td></td>
<td>N1 Latency</td>
<td>0.00152</td>
<td>3, 195</td>
<td>0.00051</td>
<td>1.01</td>
<td>0.3906</td>
</tr>
<tr>
<td></td>
<td>P2 Latency</td>
<td>0.00048</td>
<td>3, 195</td>
<td>0.0016</td>
<td>0.2</td>
<td>0.8963</td>
</tr>
<tr>
<td>SNR x Duration x Hearing Aid</td>
<td>N1-P2 Amplitude</td>
<td>4.4</td>
<td>3,195</td>
<td>1.4676</td>
<td>0.23</td>
<td>0.8735</td>
</tr>
<tr>
<td></td>
<td>N1 Latency</td>
<td>0.00245</td>
<td>3, 195</td>
<td>0.00082</td>
<td>1.62</td>
<td>0.1855</td>
</tr>
<tr>
<td></td>
<td>P2 Latency</td>
<td>0.00273</td>
<td>3, 195</td>
<td>0.00091</td>
<td>1.13</td>
<td>0.3377</td>
</tr>
</tbody>
</table>

Table 3.1 ANOVA Results – main effects and interactions (** indicates significant effect; p < 0.05)

3.1 Main Effect of Hearing Aid Rise Time

*N1-P2 Amplitude.* The only significant finding for this study was a main effect of hearing aid rise time on the N1-P2 amplitude when comparing across hearing aid groups (p = 0.0053; F (3, 208) = 4.36) (see table 3.1). The post-hoc analysis indicated that the N1-P2 amplitude was significantly affected by HA#1 (average rise time was 40.5 ms) and HA #2 (average rise time was 31 ms) when compared to the unaided (average rise time 19 ms)
condition. However, no significant effect of hearing aid rise time was found on N1-P2 amplitudes when comparing HA#3 (average rise time was 19.5 ms) and unaided condition (Figure 3.1). Furthermore, no significant effect on the N1-P2 amplitudes was found when comparing within the aided conditions (i.e., HA#1 vs. HA#2 vs. HA#3).

**N1 & P2 Latencies.** The ANOVA indicated no significant main effect of hearing aid rise time on N1 (p = 0.881) and P2 latencies (p = 0.9993) (see table 3.1).

![Figure 3.2](image)

**Figure 3.2** Post-Hoc analysis of main effect of hearing aid rise time – Significant effect on the N1-P2 amplitude when comparing HA#1 and HA#2 with unaided condition. However, no significant effect was found when comparing HA#3 condition with unaided condition. In addition, there was no significant effect on N1-P2 amplitudes when comparing HA#1 vs HA#2 vs HA#3. Asterisk (*) denotes significant differences with a p value of less than 0.05.
3.2 Main Effect of Duration

*N1-P2 Amplitudes.* The ANOVA indicated that there was no significant main effect of duration on N1-P2 amplitudes when comparing 120 ms stimuli with 60 ms stimuli (p= 0.153) (see table 3.1 and Figure 3.2).

*N1 & P2 Latencies.* The ANOVA indicated that there was no significant main effect of duration on N1 latencies (p= 0.5312). In addition, there was no significant main effect of duration on P2 latency was (p= 0.1441) (see table 3.1).

3.3 Main Effect of SNR

*N1-P2 Amplitudes.* No significant main effect of SNR on N1-P2 amplitudes (p= 0.3689) was found (See table 3.1 & Figure 3.3).

*N1 & P2 Latencies.* The ANOVA revealed no significant main effect of SNR on N1 latencies or P2 latencies (p= 0.9372) (See table 3.1).

3.4 SNR x Duration Interaction

*N1-P2 Amplitudes.* The ANOVA indicated no significant interaction between SNR and duration on the N1-P2 amplitudes (p= 0.9197) (See table 3.1; Figure 3.4).

*N1 & P2 Latencies.* The ANOVA revealed no significant interaction between SNR and duration on the N1 latencies (p= 0.5831) or on P2 latencies (p= 0.5335) (See table 3.1).

3.5 SNR x Hearing Aid Rise Time Interaction

*N1-P2 Amplitudes.* The ANOVA indicated no significant interaction between SNR and hearing aid rise time on the N1-P2 amplitudes (p= 0.24) (See table 3.1; Figure 3.5).
**N1 & P2 Latencies.** The ANOVA revealed no significant interaction between SNR and hearing aid rise time on N1 latencies (p = 0.5676) or on P2 latencies (p = 0.5306) (See table 3.1).

### 3.6 Duration x Hearing Aid Rise Time Interaction

**N1-P2 Amplitudes.** The ANOVA indicated no significant interaction between duration and hearing aid rise time on the N1-P2 amplitudes (p = 0.9442) (See table 3.1; Figure 3.6).

**N1 & P2 Latencies.** The ANOVA revealed no significant interaction between duration and hearing aid rise time on the N1 latencies (p = 0.3906) or on the P2 latencies (p = 0.8963) (See table 3.1).

### 3.7 SNR x Duration x Hearing Aid Rise Time Interaction

**N1-P2 Amplitudes.** The ANOVA indicated no significant interaction between SNR, duration, and hearing aid rise time on the N1-P2 amplitudes (p = 0.8735) (See table 3.1; Figure 3.7).

**N1 & P2 Latencies.** The ANOVA revealed no significant interaction between SNR, duration and hearing aid rise time on the N1 latencies (p = 0.1855) or on the P2 latencies (p = 0.3377) (See table 3.1).
Chapter 4: Discussion

4.1 Main Findings

This study investigated the effects of hearing aid processing on the CAEP of normal hearing individuals. More specifically, it investigated effects of rise time, duration and SNR on the N1-P2 amplitudes and latencies of the CAEP. The only significant main effect of this study was an effect of rise time on N1-P2 amplitudes when comparing across the hearing aid conditions (i.e, unaided and three aided stimuli). After controlling for SNR, this study observed an effect of rise time when comparing HA#1 and HA#2 to the unaided condition. No significant effect was observed when comparing the amplitudes of the N1-P2 of the HA#3 and the unaided condition. This result was expected as the HA#1 and HA#2 conditions had prolonged rise times (average rise times across corresponding four conditions were 40.5 ms, and 31 ms respectively) when compared with the unaided condition (average rise time was 19 ms across all four corresponding conditions) which caused a significant decrease in the N1-P2 amplitudes. In addition, the HA#3 condition had maintained the rise time (average rise time was 19.5 ms across all four corresponding conditions) of the unaided condition, therefore, the non-significant result was expected. These findings were consistent with previous research conducted on rise time which found that as rise times increase over 30 ms the N1-P2 amplitudes decrease and latencies increase (Onishi & Davis, 1968). In contrast, Easwar, Glista, Purcell, & Scollie (2012) concluded that there was a non-significant effect of rise time on the N1-P2 amplitude and latencies; however, as mentioned previously, the hearing aid that was used in their study did not create a change in rise time that exceeded 30 ms. The current study used three different hearing aid stimuli which changed rise times to range from 20 to 59 ms, which is likely why this study
found an effect of rise time after hearing aid processing that was similar to that of Onishi & Davis (1968).

Another aspect of this study was to observe the effect of duration on the N1-P2 amplitude and latencies of the CAEP. This study used two durations, 60 ms and 120 ms, and the results indicated there was no significant effect of duration on the N1-P2 amplitude or latency. This finding was consistent with previous research, which found that stimulus durations greater than 50 ms did not affect the N1-P2 amplitude and latencies (Onishi & Davis, 1989; Picton, 2011).

To control for SNR, this study used two different blocks of stimuli, the Raw stimuli which had varied SNR and amplitudes across conditions, and an Equalized/Filtered block of stimuli which had consistent SNR and amplitudes across conditions. This study found no significant effect of SNR on the N1-P2 amplitudes and latencies (i.e., comparing Raw stimuli and Equalized/Filtered stimuli). The non-significant ANOVA results indicate that this study has insufficient evidence to support the conclusion that differences in SNR affect the CAEPs. This result conflicts with previous research which demonstrated that an increase in SNR with monaural presentation should result in a significant increase in the N1-P2 amplitude and a decrease in latency (Billings et al., 2011; Billings et al., 2009; Billings et al., 2007; Billings & Grush, 2016). However, SNRs for this current study were relatively high across all conditions with the smallest SNR being 15 dB and the largest being 60 dB. Previous studies have used much smaller SNRs, for example, in Billings et al. (2009) SNRs varied from 20 dB to -10 dB. It is possible that SNRs in this study were not poor enough to cause an overall effect of SNR when comparing Raw Stimuli with Equalized/Filtered Stimuli conditions. Therefore, it is possible that this study observed a ceiling effect of SNR on the CAEP.
In addition, this study found no significant interaction effects between two or three factors on the CAEP amplitudes or latencies. There was no significant evidence to suggest that SNR and duration further impacted the effect of rise time on the N1-P2 amplitudes or latencies. Overall, this study observed a significant decrease in N1-P2 amplitudes when hearing aid processing increased rise time to be greater than 30 ms.

4.2 Future Research

Currently, clinical systems are being marketed with claims that by using aided CAEPs, clinicians are able to determine if hearing aids are effectively set for the patient (HEARLabs, 2015). However, these systems are not based on independently validated scientific evidence. In addition, findings from this study put into question the use of CAEPs as a current tool for validation of hearing aid fittings. This study found that changes to rise time due to hearing aid processing significantly affects the N1-P2 amplitude. This significant decrease in the N1-P2 amplitude could lead to a misinterpretation of the aided CAEP. A clinician may mistake the difference as an issue of audibility rather than a change in stimulus parameter caused by the hearing aid itself. If adjustments are made to the hearing aid based on this decrease in the N1-P2 amplitude of the aided CAEP the clinician risks over-amplifying the patient. Therefore, much more research is needed to evaluate different models and manufacturers of hearing aids to develop a scientifically-supported normalized standard for what these aided N1-P2 amplitudes and latencies values should be. Without a normalized standard of the aided N1-P2 amplitude and latency, the clinically observed N1-P2 amplitudes or latencies could be the result of the hearing aid processing and not the actual response to the audibility of the sound. However, creating these standards for every hearing aid model would be very difficult as the hearing aid industry is
continuously evolving and creating new technology. This would make it challenging to have up-to-date standardized norms for each make and model of hearing aid. Currently, there is not enough research supporting the use of CAEPs as an effective measure for validation of hearing aid fittings in clinic.

Additionally, it would be important to develop the aforementioned standards on individuals with hearing loss. The physiology of the auditory system is different when comparing a normal system with that of a damaged system. Therefore, it would be imperative to determine if the effects observed in this study and in other studies (e.g., Billings, Tremblay, Souza & Binns, 2007; Billings, Tremblay & Miller, 2011; Billings et al., 2012; Jenstad, Marynewich, & Stapells, 2012) would be present in participants with hearing loss and how these stimulus parameter changes impact the CAEP of different types and configurations of hearing loss.

Furthermore, future research could continue to focus on observing the reliability and validity of using CAEPs for hearing aid validation by comparing subjective or behavioral validation methods (e.g., HINT scores, or Questionnaires) to CAEP methods. There have been studies that have observed a significant correlation between these two measures of validation (Korczak, Kurtzberg, & Stapells, 2005; Golding, Pearce, Seymour, Cooper, Ching, & Dillon, 2007). It would be important to continue to explore this correlation prior to using CAEPs clinically for validation. This could help ensure that aided CAEPs are an effective and efficient tool in the validation of hearing aid fittings.

Until more studies are conducted, using CAEPs to validate hearing aid prescription should be done with extreme caution.
4.3 Limitations

This study observed the effects of hearing aid processing on individuals with normal hearing. It is important to note that the physiology of a normal auditory system is different from that of impaired auditory systems. Therefore, these results cannot be directly generalized to individuals with hearing loss. More research should be conducted to see whether or not changes in stimulus parameters due to hearing aid processing affect the CAEPs in individuals with elevated hearing thresholds. This is important because the validation of hearing aid fittings will be conducted on individuals with hearing loss and the effects that are seen in this study may not be observed in those with hearing loss. In addition, because there is large variability in hearing loss configurations and degrees among the hearing-impaired population, the variability in aided CAEPs could also be very large. This will likely be a substantial limitation to any study attempting to validate using CAEPs for adjusting hearing aids.

4.4 Conclusion

The purpose of this study was to investigate the effects of hearing aid processing on CAEPs of normal hearing individuals. The results of this study indicated that hearing aid processing did affect the CAEP. Changes in rise time due to hearing aid processing was a significant factor affecting the changes observed in the N1-P2 amplitudes. Thus, different hearing aid processors can significantly alter the stimulus being imparted on the tympanic membrane and further up the auditory system, eventually altering the recorded CAEP. Without measuring how the signal input is altered by the hearing aid, it would be difficult to determine whether smaller CAEP amplitudes were due to hearing aid processing (non-physiological effects) or due to less cortical neural firing (physiological effects). Measuring the hearing aid
output inside the ear canal could also help determine whether or not the hearing aid significantly altered the signal input in a way that would affect the CAEP. Much research would need to be conducted before being able to confidently use CAEPs for clinical validation of hearing aid fittings. However, future research should continue to evaluate the error difference between aided CAEPs validation methods and behavioral validation measures of hearing aid fittings to get a better sense of the reliability of CAEPs in the validation of hearing aid fittings.
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