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A comparison of the LS CE-Chirp and click evoked auditory brainstem response stimuli for neuro-diagnostic assessment in order to determine the preferable stimulus

A dissertation submitted in fulfilment of the degree (MA) Audiology

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Declaration of originality

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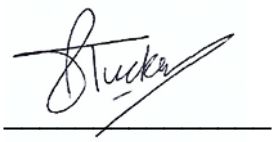
I, (Paige Tucker) hereby declare that this research dissertation is my own work. Where secondary material is used, it has been carefully acknowledged and referenced in accordance with the requirements stipulated by the University of Pretoria.

I understand what plagiarism is and am aware of the University of Pretoria's policy in this regard.



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Paige Tucker Date of declaration

Student number: 15032052

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List of key words

Auditory brainstem response

ABR

Click

LS CE-Chirp

Neuro-diagnostic

Neurological ABR

List of abbreviations

ABR	Auditory Brainstem Response
AEP	Auditory Evoked Potentials
dB	Decibels
dBnHL	Decibels Normalised Hearing Level
DPOAE	Distortion Product Otoacoustic Emissions
DPNF	Distortion Product Noise Floor Difference
Hz	Hertz
kΩ	Kilo Ohms
ms	Milliseconds
nV	Nanovolts
OHC	Outer Hair Cells
SD	Standard Deviation
SNR	Signal-to-Noise Ratio
uV	Microvolts

Abstract

Purpose:

To compare LS CE-Chirp and click evoked neuro-diagnostic auditory brainstem responses (ABR) for the purpose of determining the preferable stimulus for assessment. This is necessary for the improvement of neural synchrony and compensation for the delay of the sound wave whilst it travels through the cochlea. This will facilitate more successful, efficient and effective neurological ABR assessments.

Method:

This was a within subject comparative, exploratory research design. Participants included 34 normal-hearing individuals (aged 18-25 years, mean age 22.12 years). A comparison was completed between the ABR wave formations evoked by the click and LS CE-Chirp stimuli at 80 dBnHL at stimulus repetition rate of 27.4 Hz and 61.1 Hz with maximum permissible residual noise levels of 40 nV.

Results:

The LS CE-Chirp evoked ABR displayed later absolute latencies and shorter interpeak latencies compared to the click-evoked ABR. Significantly larger amplitudes were consistent for the LS CE-Chirp wave formations ($p<0.001$) with the exception of the wave I for the rarefaction polarity. Residual noise levels were consistently higher for the LS CE-Chirp stimuli, however, there was no correlation present between the amplitudes and the comparative residual noise levels.

Conclusions:

The LS CE-chirp stimulus elicited considerably larger waveform amplitudes, which facilitate more accurate and timely ABR assessments compared to the click. The lack of correlation between amplitude and residual noise levels suggested independence of residual noise levels, and therefore were likely due to the increased neural synchrony inherent to the chirp stimuli. The click stimulus is still advocated for during neuro-diagnostic assessments as despite the larger LS CE-Chirp amplitudes, further

research regarding the correlation with auditory-neural pathology is required before the routine use of the LS CE-Chirp stimulus can be advocated over the well-established click stimulus for neuro-diagnostic purposes.

1. Introduction

“Since its inception in the late 1960s, the Auditory Brainstem Response has been an invaluable diagnostic tool for audiologists.” - Amy K. Winston, AuD

The auditory brainstem response (ABR) is the synchronized firing of neural action potentials in response to an acoustic stimulus (Cargnelutti, Cóser, & Biaggio, 2017). In normal hearing individuals, the ABR yields five to seven distinguishable waveforms characterised by Roman numerals I-VII (Cargnelutti, Cóser, & Biaggio, 2017). These waveforms are evaluated based on their amplitude, as well as latency and interpeak latency, and are used as an objective analysis of retro-cochlear integrity. Predictable variations of the waveform features in response to changes in the auditory stimulus, including intensity, rate and polarity, provide diagnostically significant information about the presence and the type of pathology (Winston & Stoner, 2013). The ABR records responses of the neural pathway to sound, and is used in the assessment of auditory system integrity (Keesling, Parker, & Sanchez, 2017). It is clinically used to estimate hearing thresholds of adults and infants and is a useful measure to detect nervous system disorders at a peripheral and central level. Additionally, it can also be used as a means to test populations where behavioural testing may be unreliable or unattainable. This includes young children and babies as well as difficult-to-test populations (Winston & Stoner, 2013). The level of the patients’ awareness does not affect the ability to perform an accurate and reliable ABR, for example small children may be tested reliably during a natural or a sedation-induced sleep. Moreover, the assessment is also unaffected by most medications (Hyvärinen, 2012). However, there are some patient variables that may have noteworthy effects on the latency and the amplitude of the ABR waveform recordings. These variables include core temperature, gender, as well as age (Katz, Chasin, English, Hood, & Tillery, 2005). For example, a decrease in core temperature results in an increase in ABR absolute latencies and an increase in ABR interpeak latencies (Katz et al., 2005). Another example is that female subjects tend to exhibit significantly shorter absolute latencies and interpeak latencies, as well as significantly greater response amplitudes, than those of male subjects (Katz et al., 2005). A final example is in regard to the subject’s age, ABR absolute latencies, interpeak latencies, as well as amplitudes have been

shown to differ substantially depending on the age of a patient. Infant absolute latencies and interpeak latencies are considerably longer than the latencies found in adults. Additionally, older adult subjects tend to display ABR latencies that are generally longer in latency and smaller in amplitude compared to younger adult subjects (Katz et al., 2005). It should be noted that an ABR test is not a direct assessment of hearing ability, but rather it is a test of synchronous neural functioning. However, it can be used to provide an estimation of hearing sensitivity (Winston & Stoner, 2013). An ABR can be presented using a variety of stimuli. Conventionally it is presented using a click or tone burst stimulus, but more recently, using the chirp stimuli.

For conduction of the ABR assessment, the click stimulus is more frequently employed than the chirp stimulus. A click stimulus activates the entire cochlea almost instantly and is significantly shorter in duration than the chirp (Winston & Stoner, 2013). The duration of the stimulus is 0.1 milliseconds, thus it is virtually instantaneous (Hall, 2016). Such a transient stimulus produces a wide variety of frequencies in the spectrum, and hence, with a click, the ears are stimulated by a broad range of frequencies almost instantly (Rønne, Dau, Harte, & Elberling, 2012). When the resulting travelling wave reaches close to the 3000 Hz region, the hair cells are immediately stimulated, the neurons fire and the ABR ensues (Hall, 2016). This progression occurs within 5.5 milliseconds at high intensities. After the response has occurred, the travelling wave continues to progress through the cochlea toward the apical region, however, it no longer contributes to the ABR response, as the response has already transpired in the higher frequency region (Hall, 2016). Therefore, cells of the basal membrane are not stimulated at the same time and as a result, depolarization of the nerve cells cannot be completed at the same time (Ceylan, Gümüşgün, & Feratlar, 2018). This is due to the tonotopic arrangement of the cochlea, which results in the stimulation of the higher frequencies before lower frequencies, reducing neural synchrony and thus producing a smaller response regarding the amplitude of the ABR waveform (Ribeiro, Rodrigues, & Lewis, 2012). Hence, it can be seen that the click stimulus allows for synchronous nerve firing of only a very limited portion of the cochlea (Elberling & Don, 2010) as although the entire cochlea is stimulated, this stimulation is not simultaneous. Therefore, the clicks' abrupt onset,

short duration, and broad spectrum results in an asynchronous pattern of auditory nerve firing that is a consequence of the temporal delay of the sound wave travelling through the cochlea (Bargen, 2015). This condition may be described as the travelling time of the soundwave within the cochlea or “cochlear travel delay” (Ceylan et al., 2018). Thus, when using an acoustic click stimulus, the ABR is presumed to be successfully evoked during the first few milliseconds of the stimulus, and is then largely unaffected by further stimulation (Dau, Wegner, Mellert, & Kollmeier, 2000). Additionally, the click stimulus does not consistently produce clearly identifiable waveform amplitudes, particularly at lower stimulation intensities. It has been proposed that the abrupt onset and frequency range of the click causes a traveling wave that decreases neural synchrony from high-to-low frequency areas, producing considerable waveform changeability (Keesling et al., 2017). Therefore, researchers set out to develop stimuli that may compensate for these limitations and thus, the chirp stimuli were developed with the intention to evaluate auditory brainstem responses and ensure synchronized stimulation of cochlea.

The improvement of neural synchrony and compensation for the delay of the sound wave whilst traveling through the cochlea is of great significance with regards to achieving the aim of more successful, efficient and effective neurological ABR assessments. For this reason, researchers developed the chirp stimuli (Elberling & Don, 2010). Chirp stimuli consists of a sweep through frequencies, either from low to high or high to low. There is more than one type of chirp, or chirp equation, available. The original CE-Chirps, developed by Claus Elberling (Hall, 2016), sought to compensate for the previously mentioned delay of the sound wave travelling through the cochlea, allowing the hair cells to depolarize at the same time. The outcome of the chirp is a simultaneous stimulation providing improved neural synchrony and, consequently, the recording of responses with considerably greater waveform amplitude recordings (Cargnelutti et al., 2017). These larger amplitudes elicited by the chirp stimuli facilitate clearer identification of waveforms and thus improve the accuracy of the evaluator’s interpretation of the ABR waveform recordings (Ribeiro et al., 2012). Unlike the click stimulus, the chirp stimuli are able to perform “temporal compensation” for the cochlear travelling wave. This compensation is made possible by delaying the higher frequency content of the stimulus until the lower frequency

traveling waves are closer to the apex of the cochlea (Petoe, Bradley, & Wilson, 2010). Here, the lower frequencies are presented first, in such a way that the lowest frequencies around 500 Hz are presented at about 5 milliseconds before the highest frequencies of around 4000 Hz (Hall, 2016). This ensures that each frequency reaches its region on the cochlear simultaneously (Hall, 2016), leading to synchronous firing of neurons that represent all the different frequencies. This concept is termed “temporal compensation” - low frequencies are presented slightly earlier than the high frequencies, leading to a significantly larger wave V amplitude response recordings as well as a more synchronised and clear response (Elberling, Callø, & Don, 2010; Hall III, 2016). Since all cochlear regions are depolarized simultaneously by chirp stimulus, the ABR wave recordings present with greater amplitudes that can be obtained in a reduced amount of time and potentially have more diagnostic power than the click stimulus (Ceylan et al., 2018; Petoe et al., 2010). Due to this improved neural synchrony, the chirp-evoked ABR has greater repeatability with larger amplitudes and better waveform morphology owing to the more defined peaks that are elicited. These qualities make the interpretation of findings more reliable (Bargen, 2015). This is advantageous as it leads to a more precise identification of wave V and the collection of recordings in a more efficient manner. The result is an ABR waveform that is larger, can be recorded in less time (Ceylan et al., 2018), and has improved diagnostic accuracy (Petoe et al., 2010). However, it should be noted that this aspect of increased synchronisation is confined to a small range of stimulation intensities (Bargen, 2015). Since the chirp was designed with the intention to delay the cochlear wave, it is compatible with levels of lower stimulation. As the levels of stimulation begin to increase, the area of cochlear-excitation expands, and the desirable effect of greater synchronization is reversed and de-synchronization results (Bargen, 2015).

Therefore, an ABR assessment may be successfully conducted using either the click or the chirp stimuli, as both can be seen to be appropriate options for effective neuro-diagnostic assessment. Seeing that either of the stimuli may be appropriate for use during retro-cochlear diagnostic assessment, naturally, the question that arises, is which of these two available stimuli would be the preferential and more efficient option for neuro-diagnostic purposes during clinical practice?

Two studies have previously been conducted in order to determine an answer to this question, however, the results of the studies proved to be conflicting. One of the studies, by Cargnelutti and colleagues (2015), compared the LS CE-Chirp to the conventional click stimulus in teenagers and adults and found the stimuli to be equally efficient in capturing an ABR at high levels of stimulation. The second study, by Keesling and colleagues (2017), analysed the i-Chirp in comparison to the click stimulus for elicitation of the neurological ABR and found the click stimuli to be the preferred option for the purposes of neuro-diagnostic assessment. The conflicting results from these two studies necessitates further research in order to determine which option is the more effective stimulus to utilize in clinical practice when performing neuro-diagnostic ABR assessments.

Through analysis, it becomes apparent that the potential reason for these opposing findings may be directly associated with the strictness of the inclusion criteria stipulated by the individual studies. Although both studies made use of normal hearing individuals, Keesling et al. (2017) made use of stricter noise and participant inclusion criterion, such as narrower age ranges and the inclusion of DPOAE's to further aid in determining candidacy, however, it should be noted that this study failed to stipulate maximum permissible residual noise levels. Therefore, by making the noise and participant inclusion criteria stricter for the study done by Cargnelutti, Coser, and Biaggio (2015), which found the click to be equally as efficient as the chirp, there may be new and different findings to the research and thus, these findings may result in more accurate and reliable data being obtained. Consequently, establishing the foundation of this research.

The ABR has several important clinical applications, one of the most important being the detection of retro-cochlear disorders such as the life threatening acoustic neuroma, which is detected via use of a rate study (Lightfoot, 1991). The ABR rate study has significant value in identifying patients with neurological dysfunction of the auditory nerve or lower brainstem (Lightfoot, 1991). This is especially important for patients with normal cochlear function in the presence of neurological dysfunction - seen in the

case of multiple sclerosis (Lightfoot, 1991). The previous two studies conducted in 2015 and 2017 failed to analyse the effects of increases in stimulus repetition rate when making comparisons between the two stimuli. An increase in stimulus repetition rate allows the examiner to identify the presence of retro-cochlear pathology through observing changes in the wave V latency. Increases in stimulus repetition rate result in latency prolongation and amplitude reduction (Lasky, 1997), thus making analysis of the ABR waveform slightly more challenging for the examiner. However, due to the larger amplitudes generated by the chirp stimuli, perhaps the chirp stimuli may be found to be the preferable and more efficient stimulus to employ during neuro-diagnostic testing, specifically featuring rate studies.

Determining the preferential stimulus for use during neuro-diagnostic assessment is a priority, especially in the context of conflicting information. Both stimuli are appropriate options to perform neuro-diagnostic testing. However, with the ideal of employing standards of “best-practice”, it follows that further research should take place. This is necessary for an in-depth analysis of the two stimuli and their uses in retro-cochlear assessment utilizing ABR technology in order to determine which stimuli may be the most suitable option. Thereby, establishing the foundation on which this study is based.

2. Methodology

2.1 Research aims

The aim of this research was to compare LS CE-Chirp and click evoked neuro-diagnostic auditory brainstem responses for the purpose of determining the preferable stimulus for use during neurological ABR assessment.

2.2 Research design

The research design was a within subject comparative, exploratory research design, as it investigated a topic for which there was a deficiency of contextually relevant information. Furthermore, comparisons were made within subjects as opposed to between subjects (Walliman, 2011). Within subject comparisons took place through the analysis and comparison of the ABR wave formations evoked by the click and LS CE-Chirp stimuli. Data collection was collected in a cross-sectional manner, as only one contact session was necessary with the participant sample to compare the click and LS CE-Chirp evoked ABR wave formations. The data obtained was quantitative data, as it was numerical in nature (Walliman, 2011).

2.3 Ethical considerations

Ethical clearance was sought from the Research Ethics Committee of the Faculty of Humanities at the University of Pretoria prior to the commencement of data collection. Only once ethical clearance was obtained from the Faculty of Humanities did data collection commence (Appendix A). Permission to conduct this study was approved by the Research Ethics Committee at the University of Pretoria (reference number: HUM20190112).

2.3.1 Consent

Written informed consent was obtained from each participant prior to commencement of testing procedures (Appendix B).

This study was carefully structured in accordance with the Declaration of Helsinki, which is used to guide medical practitioners in research involving human subjects

(Ludviksson & Lightfoot, 2013). This study was in full accordance with local research and ethical requirements.

2.3.2 Protection from harm (risks and safety considerations)

No harm nor any form of discomfort was experienced by any of the participants involved during testing procedures as there are no direct risks associated with ABR testing.

All participants were informed about the aims of this study and were given the opportunity to learn more about the study and its elements, they were also encouraged to state any questions they may have had, to which they were provided with clear and comprehensive answers.

All participants were treated in a respectful manner and all actions were in complete accordance with beneficence and non-maleficence.

2.3.3 Voluntary and informed participation

Before the commencement of the study, each participant was informed that participation in this study was entirely voluntary. It was made clear that should the participant wish to withdraw from the study or testing procedures, this may have been done so at any time. It was also made clear that the participants' decision not to continue participation would not influence the relationship or the nature of the relationship with the researchers or with the staff at the University of Pretoria, at any point in time.

2.3.4 Anticipated benefits of partaking in the study

A full pure tone assessment; diagnostic DPOAE's and an ABR assessment were conducted in a professional manner at no charge to the participant. These procedures provided the participant with in-depth insight and information into their current hearing and health status.

2.3.5 Confidentiality

Confidentiality was and is still guaranteed to the fullest extent possible by law. Personal information shared with the researchers was used for research purposes alone. Confidentiality was ensured through alphanumeric coding during processing and storage of results. Therefore, the study participants are not able to be identified in this research.

The results of the research will be stored for 15 years for archiving purposes and as reference for possible future studies (Appendix D), this is in accordance with the requirements for research in this field. Should the research gathered be needed in the future, consent will be re-requested before any information is shared.

2.3.6 Plagiarism

The study and written report are the researcher's original work. Accurate references were used to provide and supplement information. These references were acknowledged by the researcher using APA reference guidelines. A plagiarism declaration has been provided.

2.4 Research setting

All research procedures necessary for collection of data took place at the Department of Speech-Language pathology and Audiology, at the University of Pretoria, in the neurophysiology laboratory in a sound treated booth.

2.5 Participants

This study included 34 individuals, male and female, ranging from the ages of 18 to 25 years old. Only individuals who provided informed consent were considered for participation in this study (Appendix B). Strict inclusion criteria and exclusion criteria were adhered to and are stipulated below:

2.5.1 Inclusion criteria

- The participant was required to be between the ages of 18 to 25 years old. This age range was selected as changes in ABR latencies and amplitudes are typically associated with childhood (Konrad-Martin, 2012).

- Bilateral thresholds of hearing sensitivity were required to be less than or equal to 20 dB HL at all frequencies tested as this was considered normal hearing ability (British Society of Audiology, 2012; Jerger & Jerger, 1980). This was determined using air conduction testing via behavioural pure tone audiometry at the frequency range from 125 Hz to 8000 Hz. Pure tone audiometry was performed using the modified Hughson-Westlake technique (Stach, 2010) with GSI 61 Clinical Audiometer.

- Normal middle ear functioning was determined via immittance testing. Normal middle ear functioning was defined by type A tympanograms, characterized by a middle ear pressure of -50 daPa to +50 daPa, an ear canal volume of 1.0 ml to 1.4 ml and a compliance of 0.3 ml to 1.75 ml (Jerger, 1970) and normal ipsilateral and contralateral acoustic reflexes as defined by reflex thresholds 70 to 90 dB above behavioral air conduction thresholds at the corresponding frequencies (Katz, 2014). This was determined using the GSI Tympstar.

- Normal outer hair cell (OHC) functioning, determined via Distortion Product Otoacoustic Emissions (DPOAE). Normal OHC functioning is necessary to ensure functioning of the auditory system up to the level of the cochlea (Katz, 2014). The DPOAE measurements were considered normal when three or more of the six frequencies' distortion product noise floor SNR difference was equal to or greater than 10 dB HL. The DPOAE measurements were considered abnormal when three or more of the six frequencies were either reduced: the distortion product noise floor difference (DPNF) was 6 to 10 dB HL, or absent: the DPNF difference was 6 dB HL or less (James & Dhar, 2009).

2.5.2 Exclusion criteria

- The ear canal up to the tympanic membrane had no indication of otitis media, otitis externa, occluding cerumen or any other pathology of the external ear canal as this could negatively affect the reliability of results obtained due to an impedance of the sound pathway (Stach, 2010). This was ruled-out through observation of the outer ear canal by Welch Allyn otoscope.

- Middle ear infection or pathology. This would obstruct the sound pathway and lead to inaccurate, unreliable results (Stach, 2010). Middle ear pathology was rule-out via otoscopy using a Welch Allyn otoscope as well as tympanometery with the result of type A tympanograms bilaterally obtained via use of the GSI Tympstar.

- Self-reported excessive noise exposure. Noise exposure that produces temporary threshold shifts may have resulted in immediate damage to afferent synapses and long-term degeneration of auditory nerve fibres. This damage has been seen to associate with reduced ABR amplitudes at suprathreshold levels although a hearing loss may not yet be detected (Lobarinas, Spankovich, & Le Prell, 2017).

- No neurologic contraindications, including diagnosis of space-occupying lesions, diffuse lesions and eighth nerve tumours. These would have resulted in prolongation of interpeak latency/absolute latency/ degradation of waveform/ absence of waves (Keesling et al., 2017).

2.6 Materials and apparatus

2.6.1 Equipment used for participant selection

All equipment was calibrated prior to the commencement of testing procedures. The equipment and apparatus mentioned in Table 1 were used for participation collection:

Table 1. Equipment for participant selection

Equipment	Description
Welch Allyn otoscope with reusable specula	Used to visually examine the external ear canal and tympanic membrane to ensure no outer ear pathologies or abnormalities are present (Stach, 2010).
GSI Tympstar: Comprehensive middle ear tympanometery and acoustic reflexes	Diagnostic tympanometry and acoustic reflex testing was done via a probe placed inside the ear canal. This was done in order to determine middle ear functioning (by causing pressure changes inside the ear canal) and the acoustic reflex pathway (by presenting a tone into the ear canal and measuring the reflex response of the stapedius muscle) (Stach, 2010).
Audiometer: GSI 61 Clinical Audiometer with supra-aural earphones	Determining participants behavioral hearing threshold by using air conduction audiometry using the Hughson-Westlake method. Thresholds will be determined by presenting various intensities at 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz. Thresholds were defined as the lowest intensity the participant responds to 50% of the time (Stach, 2010). Normal threshold sensitivity was defined as less than or equal to 20 dB (Jerger & Jerger, 1980).
Interacoustics Eclipse EP 25 auditory evoked (AEP) response system, using the DPOAE20	Determining the integrity of the patient's outer hair cell function was important to ensure a healthy and normal functioning auditory system up to the region of the cochlear, this was successfully done via use of DPOAE's (Stach, 2010). DPOAE measurements were conducted at the following F2 frequencies (F1/F2 ratio of 1.22): 500; 1000; 2000; 4000; 6000; 8000Hz. The intensity parameters were set to 65 dB (for L1) and 55 dB (for L2) (Katz, 2014).

DPOAE = distortion product otoacoustic emissions

2.6.2 Equipment used for data collection

The equipment and apparatus mentioned in Table 2 were used for data collection:

Table 2. Equipment for data collection

Equipment	Description
Interacoustic Eclipse EP 25 auditory evoked (AEP) system; using NuPrep abrasive skin prepping gel, Ten20 electrode paste and EarTone ABR insert earphones.	Correct calibration ensured. Calibration was done prior to data collection in accordance with ISO 389-9 (2014)
Reusable gold cup electrodes	A two channel-electrode configuration was used The non-inverting electrode (Fz) was placed on the high forehead. The inverting electrode (Mi) was placed on the ipsilateral mastoid. The ground electrode (Fpz) was placed on the low forehead. The electrodes was held in place using micropore tape.

2.7 Procedures for data collection

2.7.1 Procedures for participant collection

2.7.1.1 Informed consent

All components of the study as well as the nature of the research were thoroughly explained to all potential participants. A letter of informed consent (Appendix B) was provided to ensure that the participant had a clear understanding of what to expect as well as their ethical rights. This letter of informed consent was read, completed and signed before commencement of any testing procedures. The potential participant was also given a case history form (Appendix C) to complete in order to determine whether their current health status and health history affected their potential to participate in this study. This case history was completed prior to the appointment and, when necessary, was discussed with the participant for purpose of clarification and elaboration.

2.7.1.2 Diagnostic test battery

The diagnostic test battery was conducted by the researcher, under the guidance and supervision of two qualified audiologists at the Department of Speech-Language Pathology and Audiology, University of Pretoria. The diagnostic test battery was used to determine the candidate's potential for participation in the study. This was done by determining the normal function of the inner, middle and outer ear through the use of various tests and made use of the cross-check principle throughout.

The diagnostic assessment began with an otoscopic assessment to determine the health of the outer ear, using a Welch Allyn otoscope. Immittance testing was then performed next. By using the GSI Tympstar, the functioning of the middle ear was determined through tympanometry and ipsilateral acoustic reflex testing. Results were considered normal when type A tympanograms are obtained and acoustic reflexes were 70 to 90 dB HL above pure tone thresholds at corresponding frequencies (Katz, 2014).

Diagnostic DPOAE's were performed to determine the functioning and integrity of the outer hair cells in the cochlea (Stach, 2010). These DPOAE measurements were conducted at the following F2 frequencies (F1/F2 ratio of 1.22): 500; 1000; 2000; 4000; 6000; 8000 Hz. The intensity parameters were set to 65 dB HL (for L1) and 55 dB HL

(for L2). The DPOAE measurements were considered normal when three or more of the six frequencies' distortion product noise floor SNR difference were equal to or greater than 10 dB HL. Otherwise, DPOAE measurements were considered abnormal when three or more of the six frequencies were either reduced: the distortion product noise floor difference (DPNF) was 6 to 10 dB, or absent: the DPNF difference was 6 dB or less (Katz, 2014).

Pure tone audiometry was conducted in a soundproof, double-walled booth at the Department of Speech-Language Pathology and Audiology at the University of Pretoria. A GSI 61 clinical audiometer was used to determine the participants' hearing sensitivity. This was done using the Hughson-Westlake method of threshold determination. Frequencies tested were 125 Hz to 8000 Hz at varying intensities using supra-aural headphones. Normal hearing sensitivity was defined as thresholds that are less than or equal to 20 dB HL for adults (British Society of Audiology, 2012).

2.7.2 Procedures for data collection

Once it had been determined that the criteria for participation in this study had been met, the assessments necessary for research commenced.

Once the diagnostic test battery was completed and all results had been interpreted as normal, the participant was positioned comfortably on the bed inside the soundproof booth for the ABR testing to begin. A comfortable position was ensured as this was necessary to prevent the participant from moving and thus causing interference. Therefore, patients were placed lying down on a bed in a supine position with their eyes closed/sleeping and head slightly raised using a pillow.

The electrode sites were scrubbed using Nuprep abrasive skin prepping gel so as to reduce impedance. Ten20 electrode paste was then applied to the reusable gold cup electrodes, which were then positioned correctly and secured in place using micropore tape. The non-inverting electrode (Fz) was placed on the high forehead, the inverting electrodes (Mi) was placed on the ipsilateral mastoid and the ground electrode (Fpz) was placed on the low forehead.

The ABR recording was monaural, beginning with the click stimulus presented to the right ear, then to the left ear, both times beginning with condensation polarity, followed

by rarefaction polarity and finally alternating polarity. Following recording of the click stimuli in both ears, the LS CE-Chirp stimulus was presented and recorded in the same manner. Recording only began when impedance was recorded to be below 5 kΩ. The level of presentation was set at 80 dBnHL. This process was then repeated for both ears to ensure repeatability and reliability.

Following the acquisition of bilaterally reliable neurological ABR waves, a rate study was then performed for both stimuli. Beginning with a rate study of the click stimuli in the right and then left ear, followed by a rate study of the chirp stimuli in the right and then left ear. A rate study with an increase to 61.1 Hz stimulus repetition rate should result in a Wave V latency of no later than 6.25 ms for adults as this may be indicative of a possible retro-cochlear pathology (Ackley, Herzberger-Kimball, Burns, & Balew, 2012).

Stimulus and recording parameters were set at the default clinical protocols recommended by the manufacturer of the Interacoustic Eclipse and may be found in Table 3.

Table 3. Stimulus and recording parameters

	Click stimulus	**LS CE-Chirp Stimulus**
Stimulus Parameters		
Duration	0,1 ms (milliseconds)	10.5 ms
Intensity	80 dBnHL	80 dBnHL
Transducer	Insert earphones	Insert earphones
Rate	27,4 Hz	27,4 Hz
Polarity	Rarefaction and condensation (separately)	Rarefaction and condensation (separately)
Rate Study	61,1 Hz	61,1 Hz
Rate Study Polarity	Alternating	Alternating
Recording Parameters		
Sweeps	+/- 1500 (although signal averaging continued until residual noise is less than 40 nV)	+/- 1500 (although signal averaging continued until residual noise is less than 40 nV)
Electrodes	The non-inverting electrode (Fz) was placed on the high forehead. The inverting electrodes (Mi) were placed on the ipsilateral mastoid. The ground electrodes (Fpz) were placed on the low forehead.	
Filter	High pass filter: 33 Hz Low pass filter: 3000 Hz	High pass filter: 33 Hz Low pass filter: 3000 Hz

Impedence	Below 5 kΩ	Below 5 kΩ
Residual Noise	≤40 nV (Lightfoot, Brennan, FitzGerald, & Ferm, 2018)	≤40 nV (Lightfoot et al., 2018)

2.8 Data processing

The process of wave form analysis began after the acquisition of reliable ABR waveforms. The ABR waves were labelled by two experienced audiologists to indicate wave I, III and V in order to determine both the absolute and inter-peak latencies and amplitudes of the wave form recordings. All amplitudes were measured from the peak to the following trough (Lightfoot, 1991). Waveforms were analysed in separate polarities (condensation and rarefaction) as well as in merged polarities (alternating). During analysis of the ABR rate studies conducted, the wave forms were analysed in the alternating polarity as well as separately in condensation and rarefaction, only the amplitude and absolute latency of wave V were taken into consideration.

2.9 Data analysis

The ABR waveform recordings were obtained bilaterally, beginning with the click stimulus at all polarities, followed by the LS CE-Chirp stimulus at all polarities. Waves were labelled by two experienced audiologists to indicate wave I, III and V in order to determine both the absolute and inter-peak latencies and amplitudes of the wave form recordings. All amplitudes were measured from the peak to the following trough (Lightfoot, 1991). Waveforms were analysed in separate polarities (alternating condensation and rarefaction polarities). During analysis of both the click and LS CE-Chirp evoked ABR rate studies (conducted at an increased repetition rate of 61.1 Hz), the wave forms were analysed in the alternating polarity as well as separately in condensation and rarefaction, only the amplitude and absolute latency of wave V were taken into consideration.

Data was analysed using Microsoft Excel and SPSS (IBM Corp: released 2017. IBM SPSS Statistics Version 25 for Windows). Both SD and mean values were used to describe the absolute and interpeak latencies, amplitudes, interaural difference of wave V and the recordings utilizing an increased stimulus repetition rate conducted at 61.1 Hz. A Shapiro-Wilk test was used to determine normality of the distribution of

data. The means of normally distributed data were compared using the paired sample t-test (viz. all amplitudes and absolute latencies tended to be parametric, except for the absolute latency of wave I for the LS CE-Chirp stimulus, which was non-parametric). For Non-parametric data, the Wilcoxon signed rank test was used to compare means (viz. for analysis of all residual noise levels and interaural wave V latency differences as well as majority of the interpeak latencies as these values also tended to be non-parametric). The level of significance was set to p=0.05.

Table 4 below shows which of the data obtained was parametric data and which of the data obtained was non-parametric data.

Table 4. Results of test of normality of distribution of data

Type of data	**Data obtained**	
Non-parametric data ***W*= 971 - 174; p<0.05**	**Alternating polarity**	
	Click	LS CE-Chirp
	click interwave latency wave I-III click interwave latency wave I-V click wave I amplitude click interaural difference click residual noise	chirp interwave latency III-V chirp interaural difference chirp residual noise chirp rate study wave V amplitude
	Rarefaction polarity	
	Click	LS CE-Chirp
	click wave I amplitude click interaural difference click residual noise	chirp interwave latency I-III chirp interwave latency III-V chirp interwave latency I-V chirp interaural difference chirp residual noise chirp rate study wave V amplitude
	Condensation polarity	
	Click	LS CE-Chirp
	click interwave latency wave III-V click interwave latency wave I-V click interaural difference click residual noise	chirp absolute latency wave I chirp interwave latency wave I-III chirp interwave latency III-V chirp wave III amplitude chirp interaural difference chirp residual noise
Parametric data ***W*= 989 - 810; p>0.05**	**Alternating polarity**	
	Click	LS CE-Chirp

	click absolute latency wave I click absolute latency wave III click absolute latency wave V click interwave latency wave III-V click wave III amplitude click wave V amplitude click rate study absolute latency wave V click rate study wave V amplitude	chirp absolute latency wave I chirp absolute latency wave III chirp absolute latency wave V chirp interwave latency wave I-III chirp interwave latency wave I-V chirp wave I amplitude chirp wave III amplitude chirp wave V amplitude chirp interaural difference chirp rate study absolute latency wave V
	Rarefaction polarity	
	Click	LS CE-Chirp
	click absolute latency wave I click absolute latency wave III click absolute latency wave V click interwave latency wave I-III click interwave latency wave III-V click interwave latency wave I-V click wave I amplitude click wave III amplitude click wave V amplitude click interaural difference click rate study wave V amplitude click rate study absolute latency wave V	chirp absolute latency wave I chirp absolute latency wave III chirp absolute latency wave V chirp wave I amplitude chirp wave III amplitude chirp wave V amplitude chirp rate study absolute latency wave V
	Condensation polarity	
	Click	LS CE-Chirp
	click absolute latency wave I click absolute latency wave III click absolute latency wave V click interwave latency wave I-III click wave I amplitude click wave III amplitude click wave V amplitude click interaural difference click rate study absolute latency wave V click rate study wave V amplitude	chirp absolute latency wave III chirp absolute latency wave V chirp interwave latency wave I-V chirp wave I amplitude chirp wave V amplitude chirp rate study absolute latency wave V chirp rate study wave V amplitude

The above table shows that 65.85% of the data was parametric data and therefore made up the majority of the data obtained. The click stimulus represented 55.56% of parametric data and 42.86% of the non-parametric data obtained.

Parametric data was analysed using the paired sample t-test due to the nature of the data being normally distributed. The paired sample t-test is a statistical procedure used to determine whether there is statistical evidence that the mean difference between two sets of numerical data obtained is zero (Mcgready, 2006). Non-parametric data was analysed using the Wilcoxon signed rank test due to the nature of the data being non-normally distributed. As the Wilcoxon signed-rank test does not presume

normality in the data, it may be used when the use of the paired sample t-test is seen to be inappropriate (Shier, 2004). It is used to compare two sets of scores that come from the same participant in a study. This can occur when individuals are subjected to more than one condition. Therefore, making it appropriate for use in this study as participants were subjected to two types of stimuli, namely the click and LS CE-Chirp.

2.10 Reliability and validity

Ensuring the quality of the research conducted was vital. The measure of quality in quantitative research studies can be seen in the measures of reliability and validity (Heale & Twycross, 2015).

Validity is defined as the extent to which a concept is accurately measured and the certainty that the desired concept is being measured. Validity may be ensured by taking into consideration participant comparisons, and the correct calibration of all equipment used (Heale & Twycross, 2015).

Reliability may be seen as the consistency of a measurement. Therefore, reliability may be the degree to which a research instrument and/or procedure repeatedly yields the same results if it is used in the same situation on repeated occasions (Heale & Twycross, 2015). Strong correlations in results between different occasions indicate high reliability (test re-test reliability). Increased reliability will be ensured via alternating polarity of the ABR's, as well as through strict participant inclusion criteria.

For this study, reliability and validity were taken into consideration in various areas:

- Two experienced audiologists guided the interpretation of all results and marked the wave formation recordings together.
- The use of objective testing procedures was used alongside behavioral measures.
- The use of the same test environment within a soundproof booth was ensured when testing all participants.
- The same calibrated equipment was used for all participants. Equipment is calibrated annually by the SANS 10154-1 protocol.

- To ensure clear and accurate wave forms, residual noise levels during recording were ensured to remain below 40 uV, thus it was ensured that residual noise levels did not effect results (Lightfoot et al., 2018).

3. Article

A Comparison of the Click and LS CE-Chirp Evoked Auditory Brainstem Response Stimuli for Neuro-diagnostic Assessment

Journal: American Journal of Audiology

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Submitted: Full article submitted, pending grand average results from engineer.

Note: This manuscript was edited in accordance with editorial stipulations of the journal and may show slight differences from the editorial style found in the rest of this dissertation.

Abstract

Purpose:

To compare LS CE-Chirp and click evoked neuro-diagnostic auditory brainstem responses (ABR) for the purpose of determining the preferable stimulus.

Method:

This was a within subject comparative, exploratory research design. Participants included 34 normal-hearing individuals (aged 18-25 years, mean age 22.12 years). A comparison was completed between the ABR wave formations evoked by the click and LS CE-Chirp stimuli at 80 dBnH at stimulus repetition rate of 27.4 Hz and 61.1 Hz with maximum permissible residual noise levels of 40 nV.

Results:

The LS CE-Chirp evoked ABR displayed later absolute latencies and shorter interpeak latencies compared to the click-evoked ABR. Significantly larger amplitudes were consistent for the LS CE-Chirp wave formations ($p<0.001$) with the exception of the wave I for the rarefaction polarity. Residual noise levels were consistently higher for the LS CE-Chirp stimuli, however, there was no correlation present between the amplitudes the comparative residual noise levels.

Conclusions:

The LS CE-chirp stimulus elicited considerably larger waveform amplitudes, which facilitate more accurate and timely ABR assessments compared to the click. The lack of correlation between amplitude and residual noise levels suggested independence of residual noise levels, and therefore were likely due to the increased neural synchrony inherent to the chirp stimuli. The click stimulus is still advocated for during neuro-diagnostic assessments as despite the larger LS CE-Chirp amplitudes, further research regarding the correlation with auditory-neural pathology is required before the routine use of the LS CE-Chirp stimulus can be advocated over the well-established click stimulus for neuro-diagnostic purposes.

Key words: Auditory brainstem response; ABR; Neuro-diagnostic; LS CE-Chirp; click; Neurological ABR

Introduction

The auditory brainstem response (ABR) is the synchronized firing of neural action potentials in response to an acoustic stimulus. In normal hearing individuals, the ABR yields five to seven distinguishable waveforms characterised by Roman numerals I-VII (Cargnelutti, Cóser, & Biaggio, 2017). The ABR records responses of the neural pathway to sound, and is used in the assessment of auditory system integrity (Keesling et al., 2017). It is clinically used to estimate hearing thresholds of adults and infants and is a useful measure to detect nervous system disorders (at a peripheral and central level) (Winston & Stoner, 2013). An ABR can be presented using a variety of stimuli. Conventionally, it is presented using a click or tone burst, but more recently, using the chirp stimuli.

For conduction of the ABR assessment, the click stimulus is more frequently employed than the chirp stimulus. A click stimulus activates the entire cochlea almost instantly and is significantly shorter in duration than the chirp (Winston & Stoner, 2013). The duration of the stimulus is 0.1 milliseconds, thus it is virtually instantaneous (Hall, 2016). After the ABR response has transpired, the travelling wave continues to progress through the cochlea toward the apical region of the cochlea, however, it no longer contributes to the ABR response, as the response has already transpired in the higher frequency region (Hall, 2016). This is due to the tonotopic arrangement of the cochlea, which results in the stimulation of the higher frequencies before lower frequencies, reducing neural synchrony and thus producing a smaller response (Ribeiro et al., 2012). It has been proposed that the abrupt onset and frequency range of the click causes a traveling wave that decreases neural synchrony from high-to-low frequency areas, producing considerable waveform changeability (Keesling et al., 2017). Therefore, researchers set out to develop stimuli that may compensate for these limitations and thus, the chirp stimuli were developed.

The improvement of neural synchrony and compensation for the delay of the sound wave whilst traveling through the cochlea is of great significance with regards to

achieving the aim of more successful and effective ABR assessments. For this reason, researchers developed the chirp stimuli (Elberling & Don, 2010). Chirp stimuli consists of a sweep through frequencies, either from low to high or high to low. The original CE-Chirps, developed by Claus Elberling (Hall, 2016), sought to compensate for the delay of the sound wave travelling through the cochlea, allowing the hair cells to depolarize at the same time. The outcome of the chirp is a simultaneous stimulation providing improved neural synchrony and, consequently, the recording of responses with greater waveform amplitudes (Cargnelutti et al., 2017). Larger amplitudes facilitate clearer identification of waveforms and thus improve the accuracy of the evaluator's interpretation of the ABR (Ribeiro et al., 2012). Unlike the click stimulus, the chirp is able to engage in "temporal compensation" for the cochlear travelling wave. This compensation is made possible by delaying the higher frequency content of the stimulus until the lower frequency traveling waves are closer to the apex of the cochlea (Petoe et al., 2010). This ensures that each frequency reaches its region on the cochlear simultaneously (Hall, 2016). This concept is termed "temporal compensation". Due to this improved synchrony, the chirp-evoked ABR has greater repeatability with larger amplitudes and better waveform morphology given the more defined peaks. These qualities make the interpretation of findings more reliable (Bargen, 2015). This is advantageous as it leads to a more precise identification of wave V and the collection of recordings in a more efficient manner. The result is an ABR waveform that is larger, can be recorded in less time, and has improved diagnostic accuracy (Petoe et al., 2010). Therefore, an ABR assessment may be successfully conducted using either the click or the chirp stimuli, as both can be seen to be appropriate options for effective neuro-diagnostic assessment. Seeing that either of the stimuli may be accepted in use for retro-cochlear diagnostic assessment, naturally, the question that arises, is which of these two available stimuli would be the preferential and more efficient option for neuro-diagnostic purposes?

Two studies have previously been conducted in order to determine an answer to this question, however, the results of the studies proved to be conflicting. One of the studies, by Cargnelutti and colleagues (2015), compared the LS CE-Chirp to the conventional click stimulus in teenagers and adults and found the stimuli to be equally efficient in capturing an ABR at high levels of stimulation. The second study, by

Keesling and colleagues (2017), analysed the i-Chirp in comparison to the click stimulus for neurological ABR and found the click stimuli to be the preferred option for the purposes of neuro-diagnostic assessment. The conflicting results from these two studies necessitate further research in order to determine which option is the more effective stimuli to utilize in clinical practice, when performing neuro-diagnostic tests.

Through analysis, it becomes apparent that the potential reason for these opposing findings may be directly associated with the strictness of the inclusion criteria stipulated by the individual studies. Although both studies made use of normal hearing individuals, Keesling et al. (2017) made use of stricter noise and participant inclusion criterion, such as narrower age ranges and the inclusion of DPOAE's to further aid in determining candidacy. Therefore, by making the noise and participant inclusion criteria stricter for the study done by Cargnelutti, Coser, and Biaggio (2015), which found the click to be equally as efficient as the chirp, there may be a different conclusion that may lead to more accurate and reliable data being obtained. Consequently, establishing the foundation of this research.

The ABR has several important clinical applications, one of the most important being the detection of retro-cochlear disorders such as the life threatening acoustic neuroma, which is detected via use of a rate study (Lightfoot, 1991). The ABR rate study has significant value in identifying patients with neurological dysfunction of the auditory nerve or lower brainstem (Lightfoot, 1991). This is especially important for patients with normal cochlear function in the presence of neurological dysfunction - seen in the case of multiple sclerosis (Lightfoot, 1991). The previous two studies conducted in 2015 (Cargnelutti et al., 2017) and 2017 (Keesling et al., 2017) failed to analyse the effects of increases in stimulation rate when comparing the two stimuli. An increase in stimulus repetition rate allows the examiner to identify the presence of retro-cochlear pathology through observing changes in the wave V latency. Increases in stimulus repetition rate result in latency prolongation and amplitude reduction (Lasky, 1997), thus making analysis of the ABR waveform analysis slightly more challenging for the examiner. However, due to the larger amplitudes generated by the chirp stimuli,

perhaps the chirp stimuli may be the preferable and more efficient stimulus to employ during neuro-diagnostic testing, specifically featuring rate studies.

Method

Research was conducted in a cross-sectional manner, with a within subject comparative, exploratory research design. This design was implemented as it investigated a topic for which there is a lack of contextually relevant data and made use of comparisons within the subject as opposed to between subjects (Walliman, 2011). Data was collected in a cross-sectional manner, as only one contact session was necessary with the participant sample to compare the click and LS CE-Chirp evoked ABR's. The data obtained was quantitative data, as it was numerical in nature (Walliman, 2011).

Permission to conduct this study was approved by the Research Ethics Committee at the University of Pretoria (reference number: HUM20190112). All participants were adequately informed of the study aim as well as procedures involved. Additionally, all participants signed an informed consent form, thereby agreeing to participate in the study.

Participants

Non-probability purposive sampling was used. Participants were recruited from willing volunteers at the clinic in the Speech-Language Pathology and Audiology department at the University of Pretoria. Thirty-four consenting participants were assessed (a mean age of 22.12 years; SD: 1.46; 33 female). All participants were required to have normal middle ear functioning. This was confirmed by otoscopy and the use of the GSI Tympstar to ensure type A tympanograms along with present ipsilateral reflex thresholds at 70 to 90 dB HL above pure tone thresholds at the corresponding frequencies of 500; 1000; 2000 and 4000 Hz (Katz et al., 2005). Participants were required to present with present and normal distortion product otoacoustic emissions (DPOAE's) at 1000 to 4000 Hz tested using the Interacoustics Eclipse EP 25 auditory evoked (AEP) response system, using the DPOAE20. The normal DPOAE measurements were defined by three or more of the six frequencies' SNR (signal-to-

noise ratio) difference being equal to or greater than 6 dB SPL (James & Dhar, 2009). The intensity parameters were set to 65 dB (for L1) and 55 dB (for L2) (Katz, 2014). All participants assessed presented with normal behavioural thresholds of <20 dB HL at frequencies 125 to 8000 Hz (British Society of Audiology, 2012). This was determined using air conduction testing via behavioural pure tone audiometry using the modified Hughson-Westlake technique (Stach, 2010). Pure tone audiometry testing was conducted via use of the a GSI 61 Clinical Audiometer with supra-aural headphones in a clinically approved, double walled, soundproof booth. Participants with known neurological disorders, head injuries or self-reported excessive noise exposure were excluded from this study via the use of a comprehensive case history.

Mean and standard deviation (SD) for behavioural pure tone audiometric thresholds for participants are provided in Table 1 below.

Table 5. Mean and SD of pure tone audiometry air conduction frequencies from 125 to 8000 Hz (n=65)

Frequency (Hz)	Mean (SD)
125	6.54 (4.59)
250	4.92 (4.88)
500	4.54 (4.57)
1000	5.08 (5.56)
2000	5.77 (6.00)
4000	4.31 (5.00)
8000	4.77 (5.55)

Hz=Hertz, SD= Standard deviation

Table 1 shows that all participants had pure tone thresholds well within normal range. Low SD values indicate reliable data has been obtained.

Equipment for data collection

The Interacoustic Eclipse EP 25 auditory evoked (AEP) system was used with calibration completed prior to data collection and in accordance with ISO 389-9 (2014) for presentation of the click and LS CE-Chirp stimuli. Presentation of stimuli was done via use of Eartone ABR insert ear phones. Reusable gold cup electrodes were used for recording responses.

Recording commenced only once impedance levels were below 5 kΩ. Averaging continued until residual noise levels were below 40 nV (Lightfoot, Brennan, FitzGerald, & Ferm, 2018) with a minimum of 2200 sweeps. High pass filters were set to 33 Hz and low pass filters were set to 3000 Hz. Display gain was set to remain at 200 uV. Stimuli intensity remained at 80 dBnHL with a stimulus repetition rate at 27.4 Hz and then an increased stimulus repetition rate at 61.1 Hz. Alternating, rarefaction and condensation polarities were used.

Procedure for data collection

The ABR recording was monaural, beginning with the click stimulus presented to the right ear, then to the left ear. The stimulus intensity for both stimuli was set at 80 dBnHL with a rate of 27.4 Hz with the stimulus polarity set to condensation first, followed by rarefaction. Following recording of the click stimuli in both ears, the LS CE-Chirp stimulus was presented and recorded in the same manner.

Following the acquisition of bilaterally reliable neurological ABR wave forms at the repetition rate of 27.4 Hz, the stimulus rate was then increased to 61.1 Hz (Ackley et al., 2012). Alternating stimulus polarity was used with the intensity set to remain at 80 dBnHL during testing using the increased stimulus repetition rate.

The study was conducted in the neurophysiology laboratory at the Speech-Language Pathology and Audiology Department at the University of Pretoria in a double walled soundproof booth. Participants were tested whilst in a supine position with their head slightly raised in order to facilitate relaxation of the neck musculature as this helps to minimize physiologic noise (Chertoff, Lichtenhan, & Willis, 2010). Participants were encouraged to reduce the amount of unnecessary movement and to relax whilst with their eyes closed/sleeping. The electrode sites were scrubbed using Nuprep abrasive skin prepping gel so as to reduce impedance. Ten20 electrode paste was then applied to the reusable gold cup electrodes, which were then secured using micropore tape. The non-inverting electrode (Fz) was placed on the high forehead, the inverting electrodes (Mi) were placed on the ipsilateral mastoid and the ground electrode (Fpz) was placed on the low forehead.

Analysis

The ABR waves were labelled by two experienced audiologists to indicate wave I, III and V in order to determine both the absolute and inter-peak latencies and amplitudes of the wave form recordings. All amplitudes were measured from the peak to the following trough (Lightfoot, 1991). Waveforms were analysed in separate polarities (condensation and rarefaction) as well as in merged polarities (alternating). During analysis of the ABR rate studies conducted, the wave forms were analysed in the alternating polarity as well as separately in condensation and rarefaction, only the amplitude and absolute latency of wave V were taken into consideration.

Data was analysed using Microsoft Excel and SPSS (IBM Corp: released 2017. IBM SPSS Statistics Version 25 for Windows). Both SD and mean were used to describe the absolute and interpeak latencies, amplitudes, interaural difference of wave V and the recordings utilizing an increased stimulus repetition rate conducted at 61.1 Hz. A Shapiro-Wilk test was used to determine normality of the distribution of data. The means of normally distributed data were compared using the paired sample t-test (viz. all amplitudes and absolute latencies tended to be parametric, except for the absolute latency of wave I for the LS CE-Chirp stimulus, which was non-parametric). For Non-parametric data, the Wilcoxon signed rank test was used to compare means (viz. for analysis of all residual noise levels and interaural wave V latency differences as well as majority of the interpeak latencies as these values also tended to be non-parametric). The level of significance was set to $p=0.05$.

Results

The click and LS CE-Chirp stimuli were compared through separate analysis of the alternating, rarefaction and condensation polarities. The absolute and interpeak latencies, interaural difference, amplitudes, residual noise, and increased stimulus repetition rate recordings were taken into consideration. The results are compared below in below in Table 2.

Table 6. Absolute and interpeak latencies, amplitude, interaural wave V difference and residual noise for the neurological ABR at all polarities tested (n= 65)

	Click mean (SD)			LS CE-Chirp mean (SD)		
	Alternating	**Rarefaction**	**Condensation**	**Alternating**	**Rarefaction**	**Condensation**
Neurological ABR						
Absolute latency (ms)						
I	1.45 (0.11)	1.45 (0.12)	1.48 (0.13)	1.64 (0.12)	1.64 (0.16)	1.64 (0.13)
III	3.70 (0.16)	3.70 (0.16)	3.73 (0.20)	3.77 (0.17)	3.75 (0.21)	3.77 (0.22)
V	5.47 (0.18)	5.46 (0.23)	5.50 (0.18)	5.48 (0.19)	5.46 (0.21)	5.57 (0.21)
Interpeak latency (ms)						
I-III	2.27 (0.21)	2.25 (0.16)	2.25 (0.20)	2.13 (0.15)	2.12 (0.20)	2.15 (0.20)
III-V	1.76 (0.12)	1.76 (0.17)	1.77 (0.14)	1.72 (0.18)	1.71 (0.26)	1.78 (0.22)
I-V	4.03 (0.24)	4.00 (0.24)	4.07 (0.28)	3.84 (0.20)	3.83 (0.22)	3.93 (0.21)
Amplitude (uV)						
I	0.21 (0.20)	0.24 (0.11)	0.15 (0.08)	0.24 (0.09)	0.25 (0.09)	0.25 (0.11)
III	0.20 (0.09)	0.24 (0.12)	0.18 (0.07)	0.24 (0.13)	0.26 (0.15)	0.73 (38.32)
V	0.58 (0.19)	0.61 (0.21)	0.60 (0.17)	0.70 (0.21)	0.73 (0.22)	0.71 (0.22)
Residual noise (nV)	19.16 (3.66)	26.75 (5.07)	28.28 (6.84)	22.06 (9.21)	32.28 (15.42)	30.62 (13.37)
Interaural wave V difference (n=33)	0.13 (0.13)	0.20 (0.17)	0.14 (0.12)	0.11 (0.12)	0.15 (0.15)	0.12 (0.11)
61.1 Hz stimulus rate						
Absolute latency V (ms)	5.81 (0.21)	5.79 (0.26)	5.84 (0.22)	5.91 (0.21)	5.91 (0.22)	5.90 (0.24)
Amplitude V (uV)	0.43 (0.14)	0.42 (0.13)	0.48 (0.16)	0.52 (0.17)	0.53 (0.18)	0.52 (0.18)

SD = Standard Deviation; ms = milliseconds, uV= microvolts, Hz= hertz, ABR= auditory brainstem response

The absolute latencies of the LS CE-Chirp stimulus were all slightly delayed in comparison to the click stimulus. This is also true for the increased repetition rate conducted at 61.1 Hz. The interpeak latencies were also shorter for the LS CE-Chirp versus the click stimulus. Additionally, the wave amplitudes can be seen to be consistently greater for the LS CE-Chirp stimulus. The interaural difference is slightly larger for the click than the LS CE-Chirp.

The rarefaction polarity presented with the same pattern of findings as the alternating neurological ABR waveforms. However, the absolute latency of the wave V latencies were identical with only a 0.02 ms difference in SD values.

The mean and standard deviation for the values of the condensation stimulus polarity were analysed. Again, the same pattern of findings for the alternating and rarefaction polarities were depicted for the condensation polarity. However, the interpeak latency of wave III-V was slightly more delayed for the LS CE-Chirp stimulus at this polarity.

Click and LS CE-Chirp residual noise levels were compared in order to determine whether or not there was a significant relationship present between the two stimuli. A bubble plot has been utilized as a visual depiction of the spread of data obtained. The below bubble plot depicts the relationship of residual noise levels present between the click and LS CE-Chirp stimuli for all the polarities tested, namely alternating, rarefaction and condensation polarity.

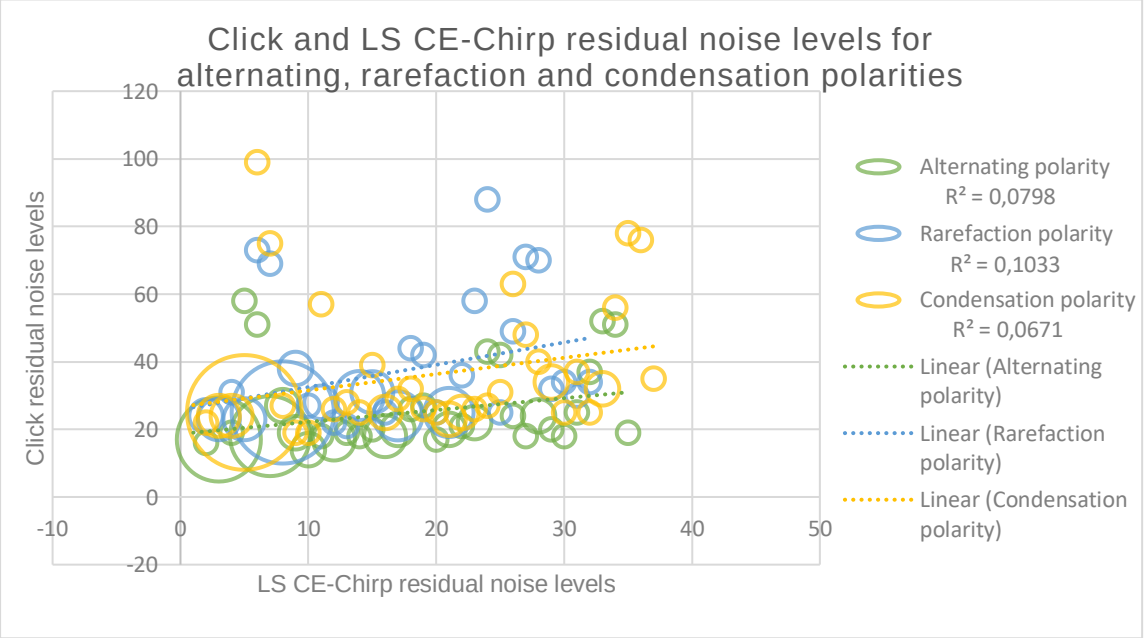

Figure 1. Click and LS CE-Chirp residual noise levels (uV) for all polarities.

The bubbles on the bubble plot depicting the alternating polarity show that there is a positive but weak correlation between the click and LS CE-Chirp residual noise levels at the recordings of all three polarities.

Scatterplots depicting the relationship between amplitude and residual noise levels for all three polarities are grouped below for a visual representation.

Figures 2 and 3 group the scatterplots that visually depict the relationship between amplitude and residual noise levels for the click stimulus at all polarities tested.

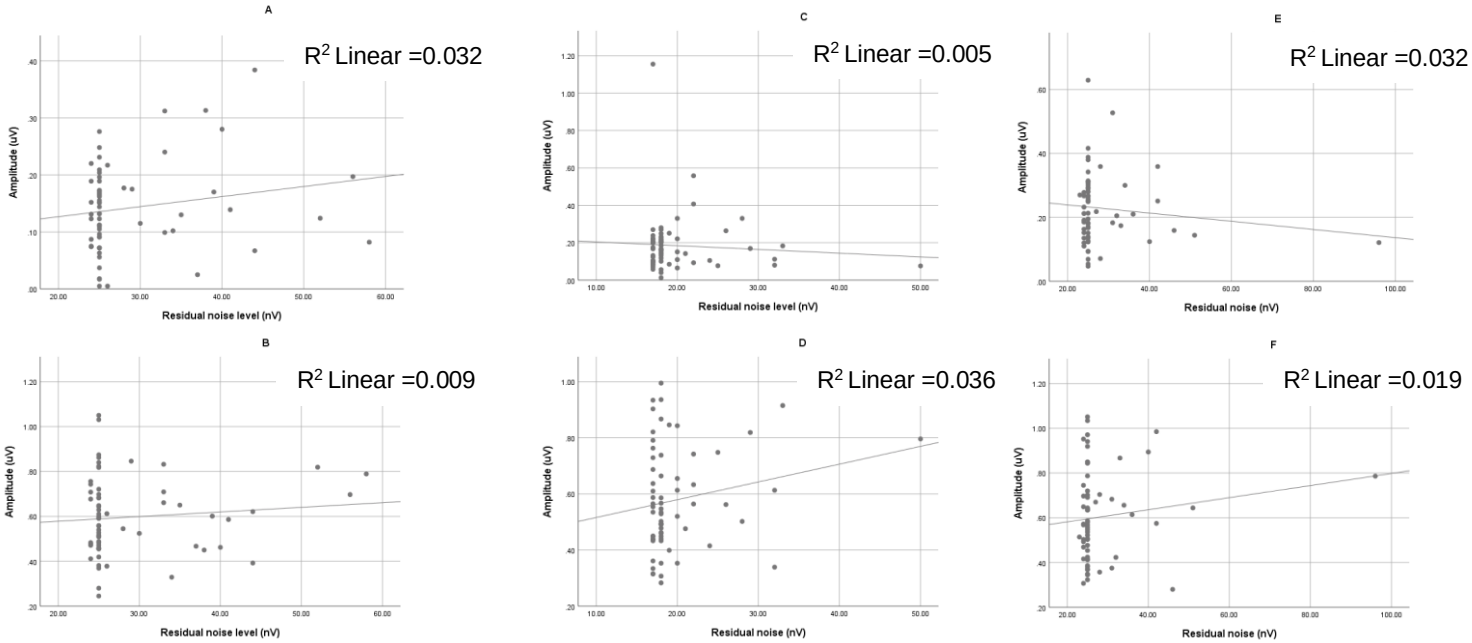

Figure 2. Scatterplots depicting the amplitude (uV) and residual noise levels (nV) for the click stimulus at all polarities.

Key:
A = amplitude of wave I and residual noise level using condensation polarity
B = amplitude of wave V and residual noise level using condensation polarity
C = amplitude of wave I and residual noise level using the alternating polarity
D = amplitude of wave V and residual noise level using the alternating polarity
E = amplitude of wave I and residual noise level using the rarefaction polarity
F = amplitude of wave V and residual noise level using the rarefaction polarity

By looking at the high level of dispersion of the data depicted in the above scatterplots, it is clear that there is a weak linear relationship between amplitude and residual noise levels. The data is both positively and negatively correlated, with majority of the data being positively correlated.

The second group of scatterplots, which may be found in Figure 3, depicts the amplitude and residual noise levels for the LS CE-Chirp stimulus at all polarities.

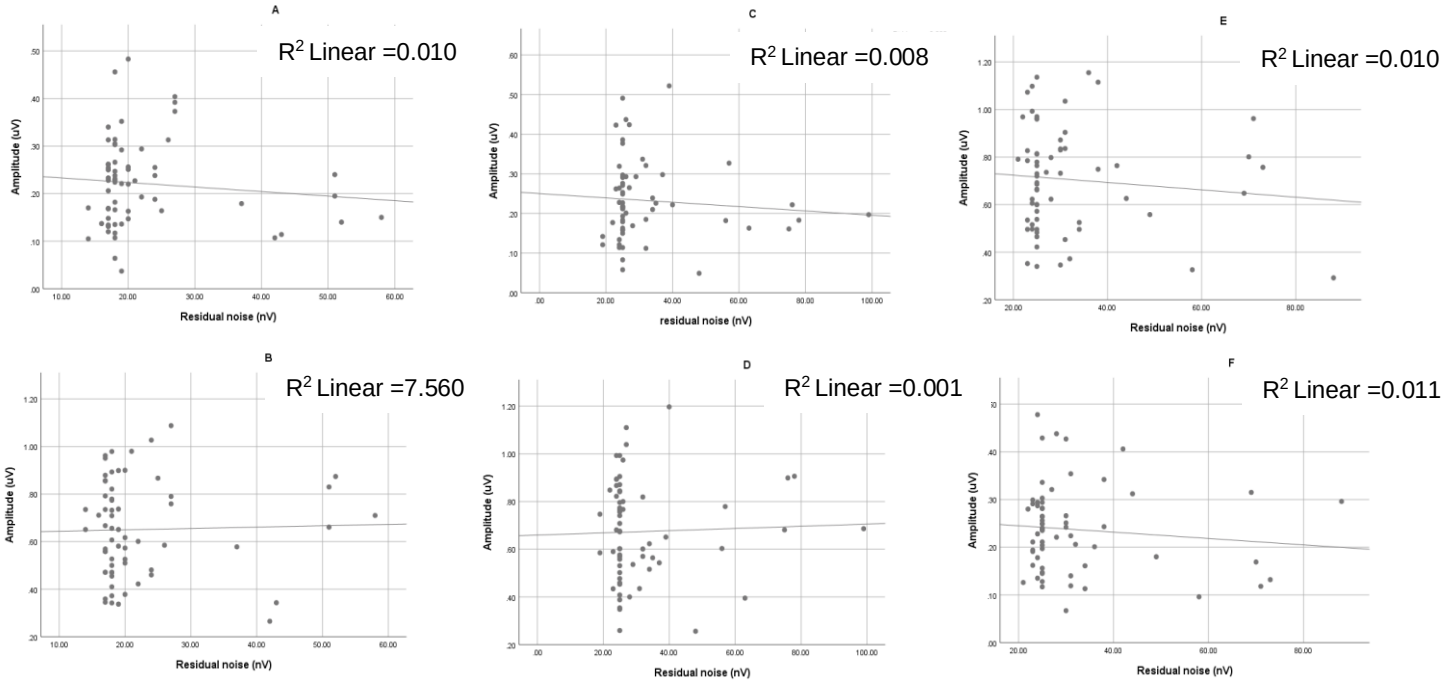

Figure 3. Scatterplots depicting the amplitude (uV) and residual noise levels (nV) for the LS CE-Chirp at all polarities.

Key:
A = wave I amplitude and residual noise level using the alternating polarity
B = wave V amplitude and residual noise level using the alternating polarity
C= wave I amplitude and residual noise level using the condensation polarity
D = wave V amplitude and residual noise level using the condensation polarity
E = wave V amplitude and residual noise level using the rarefaction polarity
F = wave I amplitude and residual noise level using the rarefaction polarity

As seen with the click stimulus, the LS CE-Chirp stimulus also depicts a high level of dispersion, indicating a weak association between the amplitude and residual noise levels for all polarities. These scatterplots are both positively and negatively correlated which is the same as the results obtained for the click stimulus. However, here the majority of data collected is negatively correlated.

Comparisons were analysed between the absolute latencies, interpeak latencies and amplitudes for the two stimuli at all polarities recorded. These comparisons are visually depicted in the bar graphs of Figure 4, Figure 5 and Figure 6, showing both stimuli as well as all three polarities tested. The bar graphs also depict error bars (representing

95% confidence interval) as well as asterisks which indicate the statistical significance of the relationship present between the two stimuli ($p<0.05$ (*); $p<0.01$ (**); $p<0.001$ (***)) at each polarity.

The bar graphs in Figure 4 display a comparison between the absolute latencies for the click and LS CE-Chirp stimuli at all polarities recorded.

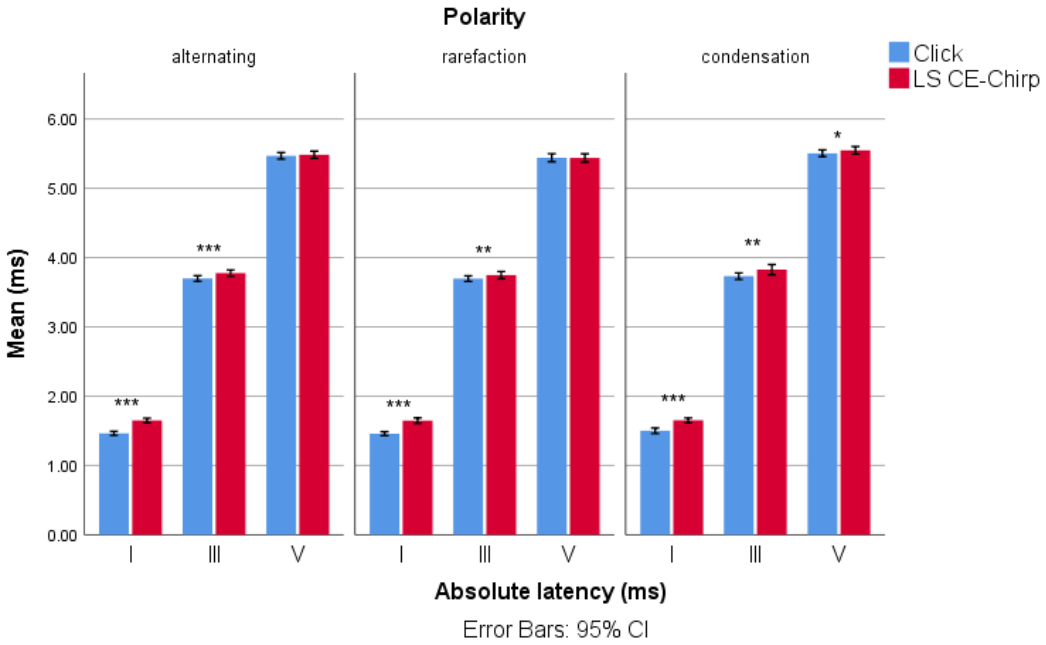

Figure 4. Bar graph depicting the mean absolute latency (ms) values for wave I, III and V for the click and LS CE-Chirp stimuli at all polarities recorded.

Figure 4 shows that highly significant differences were present between the absolute latencies for waves I ($t=-12.993$; $p<0.001$) and III ($t=-5.973$; $p<0.001$) for the alternating polarity ($p<0.001$). For the rarefaction polarity, wave I ($t=-9.895$; $p<0.001$) was highly significantly different and wave III ($t=-3.045$; $p=0.003$) was significantly different ($p<0.01$). For the condensation polarity, highly significant differences were present for wave I ($z=-5.855$; $p<0.001$), whilst wave III ($t=-2.737$; $p=0.008$) depicted a significant difference. For condensation polarity at wave V, a significant difference was present ($t=-2.023$; $p=0.047$). It is clear that the click stimulus displays a pattern of consistently earlier absolute latencies compared to the LS CE-Chirp latencies.

The bar graph in Figure 5 shows a comparison between the mean interpeak latencies for waves I-III, III-V and I-V for both the click and LS CE-Chirp stimuli at alternating, rarefaction and condensation polarities.

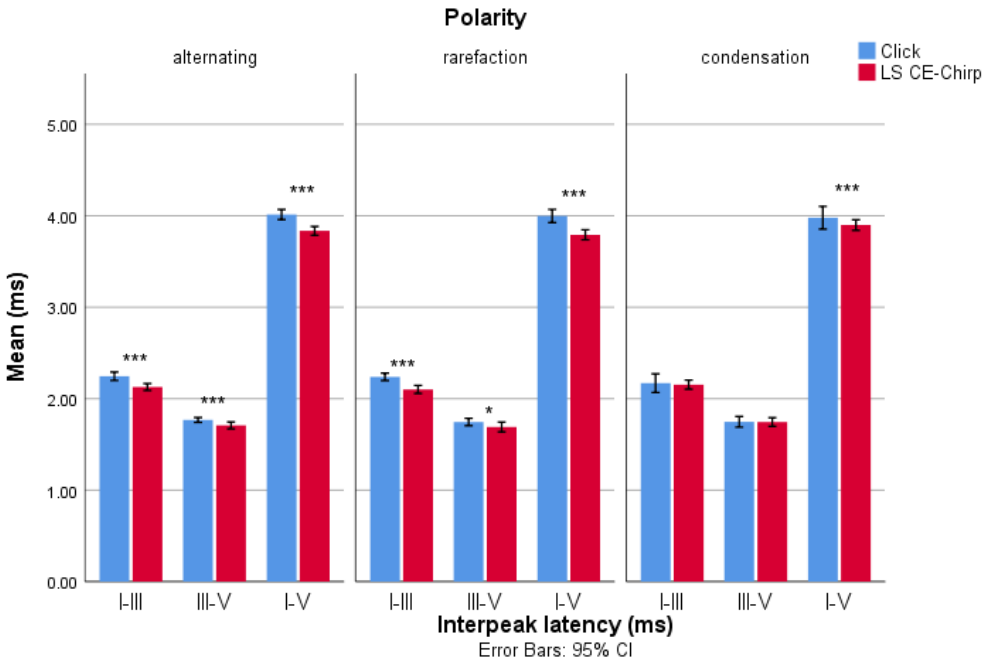

Figure 5. Bar graph depicting the mean interpeak latencies (ms) for waves I-III, III-V and I-V for the click and LS CE-Chirp stimuli at all polarities.

Figure 5 shows that the mean interpeak latency of wave I-III was consistently greater for the click stimulus than for the LS CE-Chirp at all polarities. For the alternating polarity, the waves I-III ($z=-5.899$; $p<0.001$), III-V ($z=-3.537$; $p<0.001$) and I-V ($z=-6.094$; $p<0.001$) were all highly significantly longer for the click stimulus compared to the LS CE-Chirp ($p<0.001$). For the rarefaction and condensation polarities only the interpeak latencies of waves I-III ($z=-5.608$; $p<0.001$) and I-V ($z=-3.676$; $p<0.001$) respectively, were highly significant ($p<0.001$). Wave III- V ($t=-2.276$; $p<0.05$) was significantly different ($p<0.05$) for the rarefaction polarity.

Figure 6 depicts the amplitude of waves I, III and V for the click and LS CE-Chirp stimuli at alternating, rarefaction and condensation polarities.

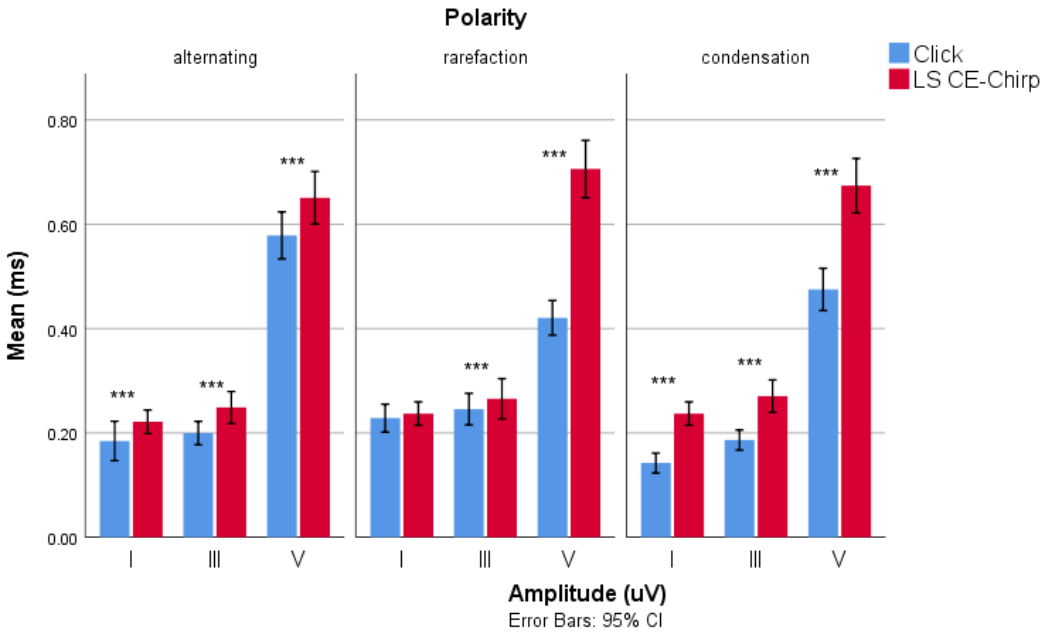

Figure 4. Bar graph depicting the amplitude (uV) for waves I, III and V for the click and LS CE-Chirp stimuli at all polarities recorded.

There was a highly significant ($p<0.001$) difference present between the click and LS CE-Chirp stimuli amplitudes at all comparisons with the exception of the wave I amplitude ($z=-0.849$; $p>0.05$) for the rarefaction polarity. The amplitudes for the LS CE-Chirp stimulus are consistently greater than the amplitudes seen for the click stimulus, this is especially so for wave V where the LS CE-Chirp stimulus amplitudes were significantly greater at all polarities (alternating: $t=-3.795$; rarefaction: $t=-5.370$; condensation: $t=-3.860$; $p<0.001$).

The amplitudes of the recordings using an increased repetition rate of 61.1 Hz were also analysed. These results were all highly significantly different (alternating: $z=-5.300$; rarefaction: $z=-5.415$; $p<0.001$; condensation: $t=-2.331$; $p<0.01$).

The interaural wave V difference was analysed for both the click and LS CE-Chirp stimulus. The interaural difference was consistently greater for the click than for the LS CE-Chirp stimulus, however this difference was not statistically significant (alternating: $z=-5.20$; rarefaction: $z=-1.483$; condensation: $z=-0.770$).

Discussion

The current study compared the click and LS CE-Chirp evoked neurological ABR. The aim of this research was to compare the LS CE-Chirp and click evoked neuro-diagnostic ABR for the purpose of determining the preferable stimulus for assessment. The stimuli were considered in terms of interpeak and absolute latencies, waveform amplitude, effect of residual noise levels and the effects of increases in stimulus repetition rates, specifically at 61.1 Hz. It was evident that the LS CE-Chirp stimulus compared more favorably to the click stimulus in terms of statistically higher amplitudes in the presence of marginally higher residual noise levels, while presenting with longer absolute latencies and shorter interpeak latencies. Similar studies have been conducted previously, with varying outcomes – either preferring the chirp stimulus (Keesling et al., 2017), or showing no specific preference between the stimuli options (Cargnelutti et al., 2017). Therefore, in the context of conflicting information, this study intended to provide clarity and determine the preferable stimulus for use during neurological ABR testing.

Amplitude

The current study showed that the amplitudes of the LS CE-Chirp wave I, III and V as well as wave V during recordings using an increase stimulus repetition rate were significantly greater than the amplitudes of the click stimulus for all polarities tested. This is in agreement with previous literature (Cargnelutti et al., 2017; Parlak, Köycü, & Hatice, 2018; Petoe et al., 2010) as larger amplitudes would be elicited by the chirp stimuli due to the optimal neural synchrony, integral to this stimulus, through use of temporal compensation (Patrikelis, Siatouni, Alexoudi, Veretzioti, & Zachou, 2018). These larger amplitudes are noteworthy as Bargen (2015) states greater amplitudes facilitate more efficient, accurate and timely identification of peaks I, III and V. Therefore, larger amplitudes are a necessity for the clinician in order to make accurate diagnoses and improve on test-time efficiency, and may potentially have more diagnostic power than the amplitudes elicited by the click stimulus (Bargen, 2015; Petoe et al., 2010).

Additionally, larger waveform amplitudes may be seen as important for interpretation of the ABR test as results are analysed through visual examination of the ABR. Therefore, it may be seen as slightly paradoxical that, for what is considered an objective assessment, a significant proportion of the waveform analysis is based on the subjective interpretation of the ABR waveforms by the clinician. Subjective interpretation may carry bias as well as inconsistencies between clinicians, however, with larger amplitudes, waveform peaks are clearer and thus, result in more accurate identification of wave formations between clinicians. Therefore larger and clearer waveform amplitudes are an important factor in reducing variability between the labelling of amplitude peaks between clinicians (McKearney & MacKinnon, 2019).

Therefore, the larger amplitudes consistently elicited by the LS CE-Chirp are a necessity if it is to facilitate accurate diagnoses, improve on test-time efficiency and thus increase the diagnostic capacity of the neurological ABR.

Residual noise

The presence of noise in ABR recordings may originate from encephalic sources (e.g. variations in brain activity caused by changes in arousal states) and non-encephalic sources (e.g. muscle/movement artefacts, blinking and electrical artefacts, such as dimmer switches) (Madsen, Harte, Elberling, & Dau, 2018). Residual noise, regardless of its origin, has the potential to give inaccurate or poor-quality wave form recordings (Madsen et al., 2018). Therefore, the current study gave close attention to residual noise levels in order to ensure accurate and reliable data was obtained and analysed. During ABR testing, averaging continued until residual noise levels were 40nV or less. This ensured clear wave form recordings that were not affected or altered by excess residual noise, as well as ensuring that the residual noise levels were comparable between stimuli.

An analysis of the correlation between the amplitudes of wave I and wave V and the residual noise levels indicated poor correlation at each polarity. This suggests that the larger LS CE-Chirp amplitudes measured were independent of the residual noise levels, and therefore likely due to the increased neural synchrony inherent to the chirp stimuli.

The current study found that residual noise levels were consistently lower for the click stimulus than for the LS CE-Chirp. Despite marginally higher residual noise levels, the LS CE-Chirp amplitudes were consistently larger than the click amplitudes. Therefore, in the presence of greater residual noise levels, the LS CE-Chirp stimulus presented with larger amplitudes and thus was not effected by the marginally higher residual noise levels. This shows that in conditions of less favourable residual noise levels, the LS CE-Chirp stimulus should be the preferred stimuli of choice.

Absolute latency

When comparing values for absolute latencies between the two stimuli, greater latencies were consistently present for the LS CE-Chirp when compared to the click stimulus at all polarities recorded (wave I: 0.16-0.19 ms; wave III: 0.02-0.07 ms; wave V: 0-0.11 ms) The absolute latencies for the LS CE-Chirp were significantly longer for both the alternating and condensation polarities ($p<0.05$). The greater absolute latency values seen whilst using the LS CE-Chirp stimuli for elicitation of the ABR have been attributed to the fact that most frequency components reach the cochlea 1.5 ms later for the chirp than the corresponding components of the click stimulus (Cargnelutti et al., 2017).

Interpeak latency

The current study found the click stimulus to have consistently larger interpeak values in comparison to those of the LS CE-Chirp. Interpeak latencies provide valuable insight into known retro-cochlear pathologies and are therefore an important aspect of the neurological ABR. The click stimulus has a considerable amount of normative data and research available on the effects of auditory neural pathologies on interpeak latencies. The researchers are not aware of such research and normative data surrounding the LS CE-Chirp. Therefore, in terms of interpeak latencies and diagnostic power, the click stimulus compares favourably to the LS CE-Chirp stimulus.

Wave V at an increased stimulus repetition rate

An increase in stimulus repetition rate, as may be used in a rate study, was included in this research. During comparison of the recordings using an increase in stimulus repetition rate conducted at 61.1 Hz, it was deduced that both the click and LS CE-Chirp stimuli displayed reductions in waveform amplitude. This is to be expected as an increase in stimulus repetition rate causes ABR waveform amplitude reduction (Lasky, 1997). However, the current study shows that with an increase in stimulus repetition rate, although amplitude reduction is present, the LS CE-Chirp stimulus recordings are less effected than the click stimulus recordings. The LS CE-Chirp stimulus consistently presented with statistically larger amplitudes at all polarities ($p<0.001$). This is noteworthy as rate studies play a vital role in the detection and diagnosis of multiple retro-cochlear pathologies (Lightfoot, 1991), and rely on visual identification of waveform amplitudes for accuracy of these diagnoses. The importance of large amplitudes cannot be overstated and is expressed throughout this discussion as well as in other research (Bargen, 2015; Keesling et al., 2017). The reduction in waveform amplitude seen during conduction of rate studies creates an unavoidable challenge for the clinician in identifying waveform peaks. However, this challenge may be minimized by employing the LS CE-Chirp stimulus, as the larger amplitudes facilitate efficient and accurate identification of waveform peaks. Therefore, making it preferable to the click stimulus during neurodiagnostic assessment utilizing increased stimulus repetition rates.

Limitations

As the participants in this study comprised only of adults, findings cannot be applied to other populations. Therefore, the findings of this study cannot extend to the pediatric population, namely those younger than three years of age. This is due to factors, such as maturation, that may lead to dissimilar ABR findings (Patrikelis et al., 2018).

Participants in this study were gender matched, however, the differences in the ABR recordings between male and female individuals were not accounted for in the current study. It is known that gender differences may cause disparities between ABR recordings, especially regarding absolute latencies at high stimulation levels, with females having significantly shorter latencies (Zakaria, Wahab, Maamor, Jalaei, & Dzulkarnain, 2019).

Although consensus on waveform analysis between two experienced audiologists was required, inter-rater reliability was not measured and therefore was not quantified.

Conclusion

Both the LS CE-Chirp and the click stimulus are appropriate options for obtaining the auditory brainstem response waves I, III and V. The current research showed statistically larger amplitudes were elicited when using the LS CE-Chirp stimulus compared to the click stimulus at all waves with the exception of wave I using rarefaction polarity, facilitating a more accurate and timely identification of wave formations. Highly significantly larger amplitudes were also recorded with increased stimulus repetition rates. The lack of correlation between the amplitudes and the comparative residual noise levels suggests that larger LS CE-Chirp amplitudes were independent of the residual noise levels, and therefore were likely due to the increased neural synchrony inherent the chirp stimuli. Therefore, although this study identified advantages of the LS CE-Chirp over the click stimulus, it does not discourage use of the click stimulus due to the lack of large-scale normative data regarding known neurological pathologies. Thus, further research is necessary before the routine use of the LS CE-Chirp stimulus can be advocated over the click stimulus for diagnostic assessment.

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4. Summary and conclusion

4.1 Summary of study findings

This study found that the amplitudes of the ABR waves elicited by the LS CE-Chirp were considerably greater than the amplitudes of waveforms elicited by the click stimulus. These larger LS CE-Chirp amplitudes were also found when utilizing an increased stimulus repetition rate of 61.1 Hz. Larger waveform amplitudes facilitate more accurate and time-efficient testing (Bargen, 2015) and therefore highlight a noteworthy advantage of the LS CE-Chirp over the click stimulus.

An analysis of the correlation between the amplitudes of wave I and wave V and the comparable residual noise levels indicated poor correlation at each polarity. This suggests that the larger LS CE-Chirp amplitudes measured were independent of the residual noise levels, and therefore likely due to the increased neural synchrony inherent to the chirp stimuli.

Thus, this research showed noteworthy advantages of the LS CE-Chirp over the click stimulus. However, due to the current limitations in the diagnostic abilities of the LS CE-Chirp owing to a lack in research regarding large-scale normative data correlating with absolute and interpeak latencies, further research is a necessity before the LS CE-Chirp may be advocated over the well-established click stimulus for routine use in neuro-diagnostic ABR assessments.

4.2 Clinical implications

This study showed that the LS CE-Chirp elicited considerably larger waveform amplitude recordings compared to the click stimulus. This is noteworthy as larger waveform amplitudes facilitate more accurate and time-efficient identification of the ABR waveform peaks, and may potentially have improved diagnostic power than the amplitudes elicited by the click stimulus.

However, the current study recommends that the click stimulus continue to be employed during neurodiagnostic assessment utilizing ABR technology. This is due to the limited research available and thus its limited diagnostic abilities.

The LS CE-Chirp may eventually be advocated for routine use during neuro-diagnostic assessment. This is due to its capacity to elicit considerably larger waveform amplitudes and thus provide results in a more time-efficient manner (Bargen, 2015). These larger amplitudes compared to those of the click-evoked ABR were also elicited during testing using an increased stimulus repetition rate, similar to that which may be found in a rate study. Rate studies play an important role in diagnostic assessments as it has significant value in identifying patients with neurological dysfunction of the auditory nerve or lower brainstem (Lightfoot, 1991). Therefore, larger amplitudes during conduction of rate studies is valuable to the clinician during clinical practice.

The click stimulus consistently presented with lower residual noise levels. This study showed that the residual noise levels present for the two stimuli gave no contribution to the considerable differences in amplitude. The larger LS CE-Chirp amplitudes are not attributed to the marginally higher residual noise levels if residual noise levels are below the maximum permissible levels for this study, namely 40 nV. Rather, the improved amplitudes stem from the improved neural synchrony inherent to the LS CE-Chirp due to the unique ability of the chirp stimuli to perform temporal compensation.

However, the LS CE-Chirp presented with shorter interpeak latencies and longer absolute latencies compared to the click stimulus. Therefore, more research is required regarding normative data before routine use of the LS CE-Chirp stimulus may be advocated. Thus, due to the current diagnostic limitations of the LS CE-Chirp owing to the lack of large-scale normative data correlating to the interpeak and absolute latencies, this study recommends that the well-established click stimulus continue to be employed during neuro-diagnostic assessment, especially if concerns regarding possible brainstem pathology arise.

4.3 Critical evaluation

A critical evaluation is necessary in order to determine the value of the research findings. This is helpful in recognising opportunities for further research and is important for interpretation of findings within the framework of both its strengths and limitations.

4.3.1 Study strengths

- The analysis of data collected was completed by two experienced audiologists so as to avoid bias and increase accuracy and reliability of the study findings.

- This study ensured that all participants were between the ages of 18 to 25 years old. This served to account for the disparities in found in ABR waveform recordings related to age differences. ABR absolute and interpeak latencies, as well as amplitudes differ substantially depending on the age of the participant. Infant absolute and interpeak latencies are considerably longer than those found in adults. Additionally, older adult subjects tend to have ABR latencies that are generally longer in latency and smaller in amplitude compared to younger adult subjects (Katz et al., 2005). Previous studies compared the LS CE-Chirp and click stimuli using ABR recording from both adults and teenagers (Cargnelutti et al., 2017). Therefore, the stricter inclusion criteria employed in this study served to prevent inaccuracies regarding age disparities.

- This study included DPOAE's in order to determine participant candidacy. DPOAE testing is a highly sensitive measure in identifying cochlear pathology and hearing loss (Suri, Gupta, Kotwal, & Kotwal, 2018). Therefore, the use of DPOAE's in determining candidacy ensured those with cochlear pathologies and/or hearing loss were filtered out and excluded from this study. Additionally, previous research failed to use DPAOE's to aid in determining participant candidacy (Cargnelutti et al., 2017).

- In order to ensure both accuracy and reliability of waveform recordings during the comparison of the click and LS CE-Chirp stimuli, the residual noise levels were kept strictly below 40nV throughout testing. Previous research failed to take residual noise levels into consideration and did not specify maximum residual noise levels (Keesling et al., 2017)

- Testing commenced only once electrode impedance was below 5 kΩ, this is in contrast to other studies, some of which began testing with electrode impedances as high as 7kΩ (Keesling et al., 2017).

- In order to ensure that residual noise levels were not influencing the amplitudes of the waveform recordings for both the click and LS CE-Chirp, this study correlated residual noise levels and amplitude. This is important to note as previous studies overlooked the effect of residual noise levels on comparative amplitudes reported (Cargnelutti et al., 2017).

- Testing of participants was performed in a soundproof both so as to substantially reduce the negative effects of high levels of background noise.

4.3.2 Study limitations

- This research study comprised only of adults between the ages of 18 to 25 years. Therefore, these findings cannot be applied to other populations such as those younger than three years of age. This is due to factors (such as maturation) that may lead to dissimilar ABR findings (Patrikelis et al., 2018).

- Participants in this study were gender matched, however, the differences in the ABR recordings between male and female individuals were not accounted for in the current study. It is known that gender differences may cause disparities between ABR recordings, especially regarding absolute latencies at high stimulation levels, with females having significantly shorter latencies (Zakaria, Wahab, Maamor, Jalaei, & Dzulkarnain, 2019).

- Although consensus on waveform analysis between two experienced audiologists was required, inter-rater reliability was not measured and therefore was not quantified.

4.4 Future research recommendations

- Although participants were gender matched, differences in the ABR recordings between male and female individuals should be investigated further in the context of comparing these two stimuli.

- This study could be extended into the paediatric population of younger than three years of age in order to determine whether the findings may apply these to younger generations as well.

- Normative data for the LS CE-Chirp stimuli should be explored further, this is especially important for patients with existing pathologies. By correlating interpeak latency and absolute latency normative data with known neurological pathologies, the value of the LS CE-Chirp stimulus for use during neuro-diagnostic assessment will significantly improve. Once large-scale normative data is available for the LS CE-Chirp, routine use during diagnostic assessment may be advocated.

4.5 Conclusion

This study showed that both the LS CE-Chirp and the click stimulus are appropriate options for use when performing neurological ABR assessments. The current research showed that statistically larger waveform amplitudes were elicited when utilizing the LS CE-Chirp stimulus than compared to the waveform amplitudes of the click stimulus at all waves with the exception of wave I using the rarefaction polarity. Larger amplitudes facilitate more accurate and time-efficient acquisition and identification of waveform recording peaks. Highly significantly larger amplitudes were also recoded with an increased stimulus repetition rate, similar to that which may be utilized during a rate study. Increasing the stimulus repetition rate is known to exhibit considerably reduced waveform amplitudes, potentially making waveform identification more challenging for the examiner. However, by employing the LS CE-Chirp stimulus during rate studies, this challenge may be minimized by the larger amplitudes that are elicited. The lack of correlation between the amplitudes and the comparative residual noise

levels suggests that larger LS CE-Chirp amplitudes were independent of the residual noise levels, and therefore were likely due to the increased neural synchrony inherent the chirp stimuli, through its ability to perform temporal compensation. therefore, although this study identified advantages of the LS CE-Chirp over the click stimulus, it does not discourage the use of the click stimulus during neuro-diagnostic assessments. This is due to the lack of normative data available for the LS CE-Chirp regarding known neurological pathologies. Thus, further research regarding large-scale normative data regarding absolute and interpeak latencies of the LS CE-Chirp and how these values may correlate to known neurological pathologies is necessary before the routine use of the LS CE-Chirp stimulus can be advocated over the click stimulus for neuro-diagnostic purposes. Additionally, it is recommended that further research take place in order to compare and analyze the LS CE-Chirp and click evoked neurological ABR waves in participants with retro-cochlear disorders.

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Appendices

Appendix A: Ethical clearance

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Humanities 100
1919 - 2019

Research Ethics Committee

6 February 2019

Dear Ms Tucker

Project:	**A comparison of the LS CE-Chirp and click evoked auditory brainstem response stimuli for neuro-diagnostic assessment in order to determine the preferential stimulus**
Researcher:	**P Tucker**
Supervisors:	**Dr L Biagio de Jager and Dr B Heinze**
Department:	**Speech-Language Pathology and Audiology**
Reference number:	**15032052 (HUM20190112)**

Thank you for the application that was submitted for ethical consideration.

I am pleased to inform you that the above application was **approved** by the **Research Ethics Committee** at a meeting held on 31 January 2019. Data collection may therefore commence.

Please note that this approval is based on the assumption that the research will be carried out along the lines laid out in the proposal. Should the actual research depart significantly from the proposed research, it will be necessary to apply for a new research approval and ethical clearance.

We wish you success with the project.

Sincerely

Prof Maxi Schoeman
Deputy Dean: Postgraduate and Research Ethics
Faculty of Humanities
UNIVERSITY OF PRETORIA
e-mail: PGHumanities@up.ac.za

cc: Drs L Biagio de Jager and B Heinza (Supervisors) Dr J van der Linde (HoD)

Faculty of Humanities
Fakulteit Geesteswetenskappe
Lefapha le Bomotho

Research Ethics Committee Members: **Prof MME Schoeman (Deputy Dean)**; Prof KI. Harris; Mr A Bizos; Dr L Blokland; Dr K Booyens; Dr A-M de Beer; Ms A dos Santos; Dr R Fasselt; Ms KT Govinder Andreas; Dr E Johnson; Dr W Kelleher; Mr A Mohamed; Dr C Puttergill; Dr D Reyburn; Dr M Soar; Prof E Taljard; Prof V Thebe; Ms B Tsebe; Ms D Mokalapa

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YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

Appendix B: Informed consent

Physical address:

Department of Communication Pathology
University of Pretoria
Lynwood Road
Pretoria
0002

Research conducted by: Paige Tucker, B Communications Pathology: MA Audiology student
Research supervised by: Dr. Leigh Biagio-de Jager and Dr Barbara Heinze

Dear Participant

Informed consent for participation in the research study: A comparison of the LS CE-Chirp and click evoked auditory brainstem response stimuli for neuro-diagnostic assessment

I, Paige Tucker (MA. Audiology student), would like to invite you to participate in a research study entitled, “A comparison of the LS CE-Chirp and click evoked auditory brainstem response stimuli for neuro-diagnostic assessment”.

This letter is for the purpose of providing in-depth information into this study, thereby ensuring that you are familiar with the various aspects prior to agreeing/disagreeing to participate. Your time is greatly appreciated.

Purpose of the study:

In order to obtain a master's degree in Audiology, this research project will be conducted. The research study is focused on auditory brainstem responses (ABR). Its focus, more specifically, is on the presentation stimuli which may be used to evoke this response. Here, the aim is to determine the preferable option of presentation stimuli, namely, the chirp or the click stimuli. This will be done through performing ABR tests on individuals, aged 19 to 25 years old that have met the inclusion criteria specified for this study.

Procedures:

Before testing commences, all procedures will be explained and an opportunity will be given for any questions to be answered. A detailed case history will be completed prior to the appointment (it will be sent to you, the participant, electronically. If this is not possible, a hard copy will be provided). The case history will be discussed at the initial appointment for purposes of clarification and possible follow-up questions.

In order for accurate and reliable data to be obtained, normal hearing of the candidate is essential for this study. Therefore, you will be required to undergo a full diagnostic audiological test battery and will only be considered suitable to continue participation if the test results are within normal limits. This test battery will include:

- Otoscopy: to ensure a normal ear canal and eardrum, by examining the ear canal with a light.
- Tympanometry: to ensure normal functioning of the middle ear and eardrum. Here, a probe will be placed into the ear, you may experience

a feeling of slight pressure build-up in the ear, which will disappear as soon as the probe is removed.

- Acoustic reflex testing: to measure the reflex response of the stapedius muscle in response to sound. Here sounds of various pitches will be presented via a probe in the ear canal and the reflex response will be measured.
- Pure tone testing: to ensure normal function of the auditory system from the outer ear through to the inner ear. Here, you will hear a range of beeping noises, which will initially be loud and will get softer as the test progresses. You will be expected to respond to the tone each time it is heard, by pressing the button provided.

This diagnostic test battery should take no longer than 30 minutes.

Distortion Product Otoacoustic Emissions (DPOAE's) will be conducted in order to ensure normal functioning of the cochlea (the organ of hearing). Emissions (released by the cochlea) will be recorded – this will be done twice in order to ensure that the responses obtained are reliable. Here, a probe will be placed into the ear, you will not be expected to respond to sounds heard, but rather sit as still and quietly as possible. This should take no longer than 10 minutes.

Once inclusion criteria have been met and confirmed, you will be placed on a bed and reclined comfortably with your eyes closed for the ABR testing to commence. Electrodes will be positioned behind both ears and on the forehead. The ABR recording will be conducted in one ear at a time, beginning with the click stimulus presented to the right ear, then presented to the left ear. Following recording of the click stimulus in

both ears, the chirp stimulus will be presented and recorded in the same manner. This process will be repeated in order to ensure repeatability and reliability. For this test, you can expect to hear various sounds presented to one ear at a time and you do not need to respond to these sounds. You are encouraged to be as relaxed as possible, falling asleep is common. This should take up to 45 minutes.

The results will then be analysed and interpreted and feedback will be given. Following this, an opportunity for further questions will be provided.

The entirety of this appointment should take no longer than a maximum of two hours, no follow-up appointments will be necessary.

Risks & discomforts:

No harm or discomfort will be experienced and there are no direct risks associated with ABR testing.

Benefits of participation:

A full pure tone assessment, DPOAE's and an ABR assessment will be conducted in a professional manner at no charge. These procedures will provide you with in-depth insight and information into your hearing health and status.

Participants' rights:

Participation in this study is entirely voluntary. Should you, as the participant, wish to withdraw from the study or testing procedures, this may be done at any time. Your decision to discontinue participation will not influence the relationship or the nature of the relationship with the researchers or with the staff at the University of Pretoria, either

at present or in the future. In the event of withdrawal from the study, all related data gathered will be immediately discarded. You also have the right to pause testing for any reason such as discomfort, to ask questions, etc.

Confidentiality:

Confidentiality will be guaranteed to the fullest extent possible by law. Personal information shared with the researchers will be used for research purposes alone. Confidentiality will be ensured through coding and the results of the research will be stored for 15 years for archiving and as reference for possible future studies, this is in accordance with the requirements for research in this field. Should the research gathered be needed in the future, consent will be re-requested before any information is shared.

For further questions or information please contact myself, Paige Tucker (MA Audiology student) or my supervisor, Dr. Leigh Biagio-de Jager or co-supervisor, Dr Barbara Heinze.

Paige Tucker:
079 136 9683
Paige.tucker77@gmail.com

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Faculty of Humanities
Department of Speech-Language Pathology and Audiology

Consent Form for Participation in Research Study

Name: _____ Date: _____

D.O.B: _____ ID Number: _____

Cell Number: _____ Email: _____

I, _____ herewith give my full consent to partake in this study and be evaluated by Paige Tucker, MA Audiology student. I understand that the results obtained will be used for research purposes and consent fully to this.

X _____
Please sign here

Thank you in advance!

_____
Paige Tucker
B. Communications Pathology: Audiology MA Student

_____
Dr L. Biagio-de Jager
Supervisor

_____
Dr B. Heinze
Co-supervisor

_____
Dr J. van der Linde
Acting H.O.D of Speech-Language Pathology & Audiology

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Appendix C: Case history form

Case History Form

Please provide your age and gender then indicate the following by marking the questions below with an 'X':

Age: _____

Gender:	M	F

Any history of middle ear infections:

Yes	No

Current middle ear infection:

Yes	No

History of surgery on the ears:

Yes	No

Regular or consistent exposure to excessively loud noise:

Yes	No

Family history of hearing loss:

Yes	No

Have you been diagnosed with a hearing loss:

Yes	No

Is this your first diagnostic hearing assessment:

Yes	No

Do you believe you may have a hearing loss:

Yes	No

Are you currently on any medication:

Yes	No

If yes, please specify:_____

Do you experience ringing in your ears:

Yes	No

Additional comments or information

_____

_____

_____

Appendix D: Declaration for the storage of research data and /or documents

I, the principal researcher, Paige Tucker and supervisors Dr Leigh Biagio-de Jager and Dr Barbara Heinze of the following study, titled: A comparison of the LS CE-Chirp and click evoked auditory brainstem response stimuli for neuro-diagnostic assessment, will be storing all the research data and/or documents referring to the above-mentioned study in the following department: Department of Speech-Language Pathology and Audiology.

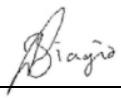
We understand that the storage of the mentioned data and/or documents must be maintained for a minimum of 15 years from the commencement of this study.

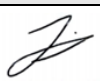
Start date of study: January 2019

Anticipated end date of study: November 2019

Year until which data will be stored: 2034

Name of Principal Researcher(s)	Signature	Date
Paige Tucker		09/11/2018

Name of Supervisor(s)	Signature	Date
Dr Leigh Biagio-de Jager		10/11/2018
Dr Barbara Heinze		10/11/2018

Name of Head of Department	Signature	Date
Dr Jeannie van der Linde		10/11/2018

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