Otoacoustic Emissions as a Part of the Test Battery for Tinnitus Diagnosis

Laura Mercieca

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Abstract

Tinnitus is a common auditory phenomenon that often occurs in the absence of measurable hearing loss, posing challenges for accurate diagnosis and early intervention. This study explored the diagnostic potential of high-frequency distortion product otoacoustic emissions (HF-DPOAEs) in detecting subclinical cochlear dysfunction in adults with tinnitus and clinically 'normal' hearing. Forty participants aged 19-40 were recruited and divided into two groups: 25 individuals with subjective tinnitus and 15 age-matched controls. All participants had hearing thresholds ≤20 dB HL (250 Hz-8 kHz) and type A tympanograms, confirming 'normal' peripheral auditory function.

DPOAEs were recorded across a frequency range of 988 Hz to 12,000 Hz. Comparative analysis of DPOAE amplitudes revealed no significant differences between groups at frequencies ≤4444 Hz. However, the tinnitus group exhibited consistent reductions in emission amplitudes at select high frequencies, with pronounced declines observed at 6154 Hz, 8000 Hz, 8889 Hz, and 10,000 Hz. While these differences did not always retain statistical significance after correction for multiple comparisons, a persistent trend emerged, suggesting diminished outer hair cell function in the tinnitus group at apical cochlear regions.

These findings suggest that HF-DPOAEs may serve as a sensitive, non-invasive measure for identifying early-stage outer hair cell dysfunction in individuals with tinnitus, even when conventional audiometry appears 'normal'. Incorporating extended-frequency OAE testing into routine audiological assessments may enhance the early detection and management of tinnitus-related cochlear changes.

Keywords: tinnitus, distortion product otoacoustic emissions, ultra-high-frequency DPOAEs, outer hair cell dysfunction, hidden hearing loss, 'normal' hearing thresholds, auditory diagnostics

Dedication

This thesis is dedicated to all those living with tinnitus;

whose daily resilience often goes unseen and unheard.

May this research be a small step toward deeper understanding, better diagnostics, and compassionate care.

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I would like to express my deepest gratitude to the people who supported and believed in me throughout this journey.

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Completing this thesis has been both a challenge and a privilege, and I am truly thankful to everyone who helped me arrive at this moment.

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Abbreviations

Abbreviation	Definition
4C- TQ	4C Tinnitus Management Questionnaire
ABR	Auditory Brainstem Response
BSA	British Society of Audiology
CN	Cochlear Nucleus
DPOAE	Distortion Product Otoacoustic Emission
EHF	Extended High Frequency
HF-DPOAE	High Frequency Distortion Product Otoacoustic Emission
HL	Hearing Level
HHL	Hidden Hearing Loss
IHC	Inner Hair Cell
IC	Inferior Colliculus
LOC	Lateral Olivocochlear (system)
MOC	Medial Olivocochlear (system)
OAE	Otoacoustic Emission
OHC	Outer Hair Cell
PTA	Pure Tone Audiometry
SD	Standard Deviation
SNHL	Sensorineural Hearing Loss
SOAE	Spontaneous Otoacoustic Emission
SFOAE	Stimulus Frequency Otoacoustic Emission
SFR	Spontaneous Firing Rate
THI	Tinnitus Handicap Inventory
TEOAE	Transient Evoked Otoacoustic Emission

Glossary

Term	Definition
Tinnitus	The perception of sound, such as ringing, buzzing, or hissing, in the absence of an external auditory stimulus. It may be temporary or chronic and is often associated with cochlear dysfunction.
Distortion Product Otoacoustic Emissions (DPOAEs)	Acoustic signals generated by the outer hair cells of the cochlea in response to two simultaneously presented pure tones (f1 and f2). DPOAEs are used to assess cochlear function, particularly outer hair cell integrity.
High-Frequency DPOAEs (HF-DPOAEs)	DPOAE responses measured at frequencies ≥8000 Hz. These are especially useful for detecting subtle or early-stage cochlear changes not evident in standard audiometry.
Outer Hair Cells (OHCs)	Sensory cells located in the cochlea that contribute to the amplification and fine-tuning of sound. OHC dysfunction is commonly linked to tinnitus and early hearing damage.
Pure-Tone Audiometry (PTA)	A behavioural hearing test used to determine an individual's hearing thresholds across a range of frequencies, typically from 250 Hz to 8000 Hz.
'Normal' Hearing Thresholds	Hearing sensitivity defined as ≤20 dB HL across standard audiometric frequencies (250 Hz-8 kHz), indicating no clinically detectable hearing loss.
Tympanometry	A test used to assess middle ear function by measuring eardrum movement in response to changes in air pressure. A Type A tympanogram indicates 'normal' middle ear function.
4C-Tinnitus Questionnaire (4C-TQ)	A validated self-report tool assessing tinnitus impact across four domains: cognitive interference, emotional distress, behavioural effects, and severity.
Signal-to-Noise Ratio (SNR)	The ratio between the strength of the DPOAE signal and the background noise. An SNR of ≥6 dB is typically considered acceptable for confirming the presence of emissions.

Audiogram	A graphical representation of an individual's hearing thresholds across frequencies, typically used to diagnose and classify hearing loss.
Hidden Hearing Loss (HHL)	A form of auditory dysfunction where individuals experience listening difficulties despite having 'normal' audiograms, often linked to cochlear synaptopathy or subclinical OHC damage.
Cochlear Synaptopathy	The degeneration or loss of synaptic connections between inner hair cells and auditory nerve fibres, often associated with noise exposure and implicated in HHL and tinnitus.

The term 'normal' is used throughout this dissertation to refer to clinically acceptable hearing thresholds (≤20 dB HL across 250 Hz–8 kHz) and tympanometric results consistent with typical middle ear function (Type A). It is acknowledged that this terminology does not imply the absence of subclinical auditory dysfunction, and that individuals classified as having "normal" hearing may still exhibit underlying cochlear or neural abnormalities not detectable through standard audiometry. The use of "normal" in this context reflects conventional clinical criteria rather than an absolute indicator of auditory health.

Chapter 1- Introduction

This chapter outlines the theoretical framework essential for comprehending the complex nature of tinnitus. It begins with an overview of tinnitus and traces the progression of how it has been understood over time. The chapter then introduces otoacoustic emissions (OAEs), which serve as the primary diagnostic tool employed in this study. It also provides a brief explanation of the fundamental properties of OAEs and explores the relationship between tinnitus and cochlear function.

1.1 Understanding Tinnitus

Tinnitus is broadly defined as the perception of sound in the absence of an external acoustic stimulus. Descriptions of tinnitus have evolved, reflecting changes in clinical and theoretical understanding. Hazell (1995) characterised it as "a sound perceived for more than five minutes at a time, in the absence of any external acoustical or electrical stimulation of the ear and not occurring immediately after exposure to loud noise". Earlier references include terms such as 'phantom auditory perception' (Jastreboff, 1990) and 'head noise' (Fowler, 1939). Kemp (1981, p. 54) described tinnitus as embracing "an infinite variety of auditory sensations that are not caused by externally applied stimulation."

Tinnitus does not constitute an independent pathological condition but is instead regarded as a symptom indicative of underlying auditory system dysfunction. A range of etiological factors have been implicated in its onset, including noise-induced hearing impairment, presbycusis, exposure to ototoxic pharmacological agents, and psychological contributors such as heightened stress and anxiety levels (Eggermont & Roberts, 2015).

Prevalence estimates vary widely, ranging from 5% and 43% in the general population, with 10% to 30% experiencing tinnitus that lasts for more than five minutes at a time (Maes et al., 2013; McCormack et al., 2016). Around 2.3% of the population, 120

million people world-wide, suffer from severe tinnitus (Jarach et al., 2022). Despite its prevalence, tinnitus remains a complex and often poorly understood condition due to the heterogeneity of its causes and manifestations.

The perception of tinnitus varies widely among individuals, manifesting as ringing, buzzing, hissing, or other sounds across various frequencies and loudness levels. While it can be temporary or chronic, tinnitus is often associated with underlying auditory dysfunction, including cochlear damage (Shapiro et al., 2021).

The impact of tinnitus on an individual's quality of life can be significant, affecting emotional well-being, concentration, sleep, and overall mental health (Henry et al., 2014). As a result, effective assessment and management of tinnitus remain crucial in audiological practice. Despite advancements in tinnitus research, diagnosis remains challenging due to the subjective nature of the condition (Kleinjung et al., 2024). Most clinical evaluations rely on patient-reported symptoms, which can be influenced by psychological and cognitive factors (Hall et al., 2018). This highlights the need for objective assessment tools to complement self-reported measures.

1.2 Otoacoustic Emissions

One promising avenue of investigation focuses on OAEs, which serve as a non-invasive technique for examining cochlear function. OAEs are low-intensity acoustic signals generated by the cochlea in response to auditory input and can be used to evaluate outer hair cell (OHC) activity (Mishra, 2010). Since tinnitus is often associated with cochlear dysfunction, particularly at the level of OHCs, OAEs may serve as a valuable component of a comprehensive tinnitus test battery (Ceranic, 1999).

The discovery and first successful recording of OAEs was achieved by David Kemp in 1978. Initially confined to specialized research environments, OAE recording techniques

have since evolved into standard diagnostic tools employed in audiological clinics across the globe. OAEs offer a unique method for directly assessing the function of sensory cells within the cochlea, marking a transformative advancement in both hearing science and clinical practice (Dhar & Hall, 2018).

Kemp later theorized that OAEs originate from the cochlea as a by-product of an active, nonlinear biomechanical process mechanism involving from the OHCs to the basilar membrane. This mechanism serves to enhance the cochlea's sensitivity to soft sounds and improves frequency selectivity by amplifying vibrations in a localized area of the cochlear partition (Kemp, 2008).

OAEs can be recorded in the ear canal either in the absence of acoustic stimulation, referred to as spontaneous otoacoustic emissions (SOAEs), or can be evoked by acoustic stimuli. These evoked types include transient-evoked OAEs (TEOAEs), distortion-product OAEs (DPOAEs), and stimulus-frequency OAEs (SFOAEs). Of these, DPOAEs are particularly relevant to this study and will be examined in greater detail.

SPOAEs are naturally occurring emissions without external stimulation, however these are not present in every individual. They have been reported across studies in approximately 60% of individuals with clinically 'normal' hearing thresholds (Levine, 2003).

TEOAEs are typically elicited using repeated broadband click stimuli, which stimulate a broad region of the basilar membrane. These emissions are captured in the short silent intervals between successive clicks (Kemp, 2002). Due to their sensitivity and reliability, TEOAEs are particularly well-suited for hearing screening applications, especially in neonatal settings, covering a frequency range approximately between 500 Hz and 4 kHz (Paludetti et al., 1999).

DPOAEs represent a specific category of evoked OAEs, generated through the nonlinear cochlear response to two simultaneously presented pure-tone stimuli, referred to as the primary tones f1 and f2, which are closely spaced in frequency (Ramos et al., 2013). The interaction of these tones leads to overlapping vibratory responses along the cochlear partition. Historically termed ‘combination tones’, DPOAEs have gained considerable clinical relevance following advancements in techniques for accurately measuring these emissions (Glattke & Kujawa, 1991). These two tones interact to produce a distortion result, and the ear canal is used to assess the response (Moulin et al., 1993). DPOAEs are frequently used to test cochlear function in greater detail at a given frequency (Kemp, 2002). DPOAEs are thought to be a quick, objective, reliable, and consistent way to assess the physiological integrity of the cochlea's OHC (Gentil et al., 2015). These OAEs are a phenomenon that can be seen in ears with mild hearing loss as well as ‘normal’ hearing ears, although they are known to be absent or less common in ears with hearing loss (Gentil et al., 2015). DPOAEs are employed in the peripheral auditory system to identify subtle changes in hearing (Riecke et al., 2020). Given that DPOAEs assess cochlear function across a broad frequency range they represent an appropriate tool for exploring the relationship between tinnitus and OHC function (Onishi et al., 2004), in this study 900-12kHz will be analysed.

SFOAEs are evoked by continuous pure tones but are less frequently used within the clinical setting. SFOAEs are mainly used in research to study cochlear tuning, OHC function and the efferent auditory system (Charaziak & Siegel, 2015).

1.3 Clinical Challenges in Tinnitus Assessment

From a clinical perspective, tinnitus assessment is challenging due to its inherently subjective nature. Unlike other auditory conditions that can be measured objectively using audiometry, tympanometry, or electrophysiological techniques, tinnitus largely relies on self-reported symptoms. While psychoacoustic tests such as pitch matching, loudness matching,

and minimum masking level testing can provide insights into tinnitus characteristics, they do not provide definitive physiological markers (Szibor et al., 2017). As a result, researchers have explored alternative objective measures to supplement standard diagnostic approaches.

While questionnaires and psychoacoustic tests provide valuable insights, they are fundamentally subjective and may be influenced by psychological factors such as stress, anxiety, or depression (Hall et al., 2018). Objective measures, including OAEs, auditory brainstem responses (ABRs), and functional imaging techniques, offer additional information that may improve diagnostic accuracy. Despite the wide range of available tests, current tinnitus assessments have notable limitations. Patient responses can be highly variable, as tinnitus perception fluctuates over time, leading to inconsistencies in self-reported assessments (Manning et al., 2019). There are no objective biomarkers that can definitively confirm tinnitus, making diagnosis more complex (Cardon et al., 2020). Furthermore, existing tests struggle to differentiate between tinnitus subtypes, as some patients experience tinnitus despite having ‘normal’ audiograms, indicating that standard audiometry alone may be insufficient for accurate evaluation (Tsang et al., 2024).

1.4 Use of OAEs in Tinnitus Assessment

The primary objective of cochlear function monitoring is the early identification of dysfunction, aiming to intervene before irreversible damage occurs to the OHCs or other cochlear components (Moore, 2007). Given the hypothesized role of OHCs in the pathophysiology of tinnitus, the evaluation of OAEs may offer a dependable method for detecting OHC dysfunction (Omidvar et al., 2016).

Several studies have reported that individuals with tinnitus may present with clinically ‘normal’ hearing thresholds up to 8 kHz when assessed through conventional Pure-Tone Audiometry (PTA), which typically employs pure tone sound stimuli (Kara et al., 2020). The

cochlear abnormality in the basal area of these people is thought to be one potential cause of tinnitus (Makar, 2021). As a result, research directs that while evaluating tinnitus patients, PTA should be extended to 16 kHz (Fabijańska et al., 2012; Vielsmeier et al., 2015; Ma et al., 2024).

Several studies have explored the relationship between OAEs and tinnitus, revealing notable findings. Research indicates that patients with tinnitus often exhibit reduced OAE amplitudes, particularly in the high-frequency range (Omidvar et al., 2016; Jedrzejczak et al., 2022). Some individuals with tinnitus but 'normal' audiograms show abnormal OAE patterns, suggesting early-stage cochlear dysfunction (Hunter, 2020). Reported differences in DPOAEs and TEOAEs responses between individuals with tinnitus and individuals without tinnitus further support the hypothesis that cochlear involvement plays a role in tinnitus generation (Fournier & Hébert, 2013).

Research has also looked into the potential hypothesis of tinnitus as a result of hyperactivity in the central auditory system in people with 'normal' hearing (Gu et al., 2010). Some studies suggest that elevated motility of the OHCs may result in elevated DPOAE levels due to hyperactivity in one or more brainstem domains produced by greater spontaneous noise, reduced inhibition, or enhanced gain (Gouveris et al., 2005; Ceranić, 2007). However other studies report that DPOAEs in individuals with tinnitus is much lower than in non-tinnitus hearing individuals over a variety of frequencies (Modh et al, 2014; Zhao et al., 2014). Research reveals that the source of OHC dysfunction may be indicated by a reduction in the amplitude of DPOAEs, possibly caused by discordant Inner Hair Cells (IHC) and OHC damage (Modh et al., 2014). OHC are more likely to sustain damage, and when this happens, they are unable to inhibit IHC function. Tinnitus is thought to be caused by this reduction in IHC inhibition (Salvi et al., 2017). Therefore, a drop in DPOAE amplitude may be the outcome of an increase in internal ear noise.

Given the role of OHCs in cochlear mechanics, OAEs offer a promising avenue for tinnitus evaluation. Since tinnitus may be associated with OHC dysfunction, even in individuals with clinically 'normal' hearing thresholds (Gu et al., 2012), the OAE amplitude and response patterns may highlight subtle cochlear abnormalities that could contribute to tinnitus perception.

1.5 Rationale for the Current Study

Despite extensive research on tinnitus, a definitive objective diagnostic tool remains elusive. Traditional assessment methods rely heavily on subjective self-reporting, which can be influenced by emotional, cognitive, and psychological factors. This subjectivity often leads to variability in clinical outcomes and challenges in standardising tinnitus assessment protocols across different populations (Hall et al., 2018). Consequently, there is a growing need for objective measures that can supplement existing tests and improve diagnostic accuracy.

While tools like the 4C- Tinnitus Questionnaire (4C- TQ) and the Tinnitus Handicap Inventory (THI) provide valuable subjective data, they lack objective physiological measures of cochlear function. OAEs address this gap by directly assessing OHC integrity, offering a complementary biomarker for tinnitus even in 'normal' hearing individuals (Ma et al., 2024).

OAEs provide a direct assessment of cochlear function, specifically the integrity of OHCs, which play a critical role in auditory processing (Girolamo et al., 2007). OHC dysfunction may be a key contributor to tinnitus perception (Haider et al., 2018). However, there is still a lack of consensus on how OAE patterns differ between individuals with tinnitus and non-tinnitus hearing individuals, particularly in cases where hearing thresholds remain within 'normal' limits. Further research in this area could bridge this knowledge gap and potentially lead to improved clinical protocols for tinnitus diagnosis. By exploring the

relationship between OAEs and tinnitus, this research aims to contribute to a more comprehensive and objective tinnitus assessment framework.

1.6 Research Aim and Objectives

Based on the current gaps in diagnostic approaches for tinnitus with 'normal' hearing thresholds, this study addresses the following research question: Can high-frequency DPOAEs (HF-DPOAEs) serve as an objective tool for identifying cochlear dysfunction in individuals with tinnitus and clinically 'normal' hearing thresholds?

The aim of this study is to evaluate the diagnostic utility of HF-DPOAEs in individuals with tinnitus and clinically 'normal' hearing. Specifically, the study seeks to determine whether DPOAE amplitudes can detect subclinical cochlear dysfunction and differentiate individuals with tinnitus from non-tinnitus controls.

The following objectives were targeted:

1. To compare HF-DPOAE amplitudes between individuals with and without tinnitus, despite clinically 'normal' pure-tone audiograms.
2. To investigate the correlation between DPOAE amplitudes and 4C-TQ scores, assessing the relationship between OHC dysfunction and tinnitus impact.
3. To assess the clinical utility of HF-DPOAEs (>8000 Hz) in distinguishing tinnitus patients from controls.
4. To explore whether specific tinnitus characteristics are associated with distinct cochlear emission profiles.
5. To investigate the role of recreational noise exposure on DPOAE amplitudes in individuals with tinnitus.

6. To examine the influence of age-related changes on the interpretation of DPOAE amplitude profiles in adults with tinnitus.

1.7 Conclusion

This chapter introduced the key concepts underlying tinnitus and its assessment, with a focus on OHC function and the role of OAEs. It outlined the clinical limitations of current diagnostic tools and presented the rationale and objectives guiding this study. The next chapter reviews existing research on the use of OAEs in tinnitus evaluation.

Chapter 2- Literature Review

This chapter explores the complex relationship between tinnitus and cochlear function, with a particular focus on outer hair cell (OHC) dysfunction and cochlear synaptopathy. Tinnitus, the perception of sound without an external stimulus, may occur even in individuals with 'normal' audiometric thresholds, indicating underlying auditory deficits undetectable by conventional tests (Liberman, 2017; Schaette & McAlpine, 2011).

The central aim of this chapter is to investigate the diagnostic potential of otoacoustic emissions (OAEs) in assessing subtle cochlear dysfunction in patients with tinnitus. Additionally, the physiological basis of tinnitus is explored, emphasizing the contributions of OHC impairment and synaptic disruptions at the auditory nerve, collectively known as cochlear synaptopathy. These mechanisms offer a potential explanation for tinnitus perception in the absence of audiometric hearing loss.

By synthesizing current findings, this review underscores the need for improved diagnostic strategies to evaluate and manage tinnitus, particularly in patients with clinically 'normal' hearing. The integration of recent literature provides a comprehensive framework for understanding how cochlear deficits contribute to tinnitus and its broader auditory consequences.

2.1 Tinnitus

Tinnitus refers to the auditory perception of sound in the absence of any external auditory stimulus. Commonly characterized by sensations such as ringing, buzzing, hissing, or whistling, the condition can manifest either intermittently or persistently (Chiari & Limb, 2018). Tinnitus is not an independent medical disorder but rather a clinical manifestation of an underlying pathological condition. It may present unilaterally or bilaterally, depending on the nature and origin of the causative factors (Han et al., 2018). One of the primary objectives

in the clinical assessment of tinnitus is to determine whether it is a symptom of a sensory disorder or pathology requiring medical intervention. In the majority of individuals with bothersome tinnitus, there is no serious underlying disease and is believed to be benign and idiopathic (Dalrymple et al., 2021). Tinnitus is frequently linked to factors such as sensorineural hearing loss (SNHL), prolonged exposure to loud noise, aging, and psychological stress (Hasson et al., 2011; Hébert et al., 2012; Mazurek et al., 2015; McKenna et al., 1991; Seydel et al., 2013). Less commonly, it may arise from other otologic conditions, neurological disorders, infections, adverse drug reactions, or other comorbidities (Yew, 2014). Nonetheless, a subset of individuals with tinnitus demonstrate clinically 'normal' hearing thresholds on standard pure-tone audiometric (PTA) evaluations (Savastano, 2008).

2.1.1 Prevalence and Demographics

Epidemiological studies highlight the widespread occurrence of tinnitus across various age groups. Prevalence rates vary, but estimates suggest that 1-14% of the global population experiences persistent tinnitus (Jarach et al., 2022). Notably, its prevalence increases with age, with higher rates observed among older individuals (Reisinger et al., 2023). The percentage of tinnitus alongside pure tone thresholds within 'normal' limits' is thought to be around 10% of all tinnitus patients (Guest et al., 2017; Wang et al., 2022).

Epidemiological, psychoacoustic, and clinical research has shown that although tinnitus is a common condition experienced by many people globally, only about 20% of those affected report it as problematic. Moreover, the intensity of tinnitus symptoms and the effectiveness of treatment do not appear to correlate with psychoacoustic characteristics such as pitch, loudness, or minimum masking levels (Jastreboff & Hazell, 2004; Hastreboff et al., 1994). These findings challenge the previously dominant notion that tinnitus is solely the result of auditory system dysfunction. These findings underpin the neurophysiological model

of tinnitus, which posits that in cases of clinically significant presentations, the auditory pathway may serve a secondary function. Instead, greater emphasis is placed on the involvement of non-auditory neural circuits, particularly the limbic and autonomic systems, which are thought to mediate the emotional and physiological responses associated with tinnitus perception (Jastreboff, 1990).

2.1.2 Aetiology and Contributing Factors

Tinnitus represents a multifaceted otological phenomenon, and despite substantial advancements in research, its underlying pathophysiological mechanisms have yet to be fully clarified (Haider et al., 2018). Current evidence suggests that both peripheral and central components of the auditory system contribute to its onset and persistence. According to Tunkel et al. (2014), tinnitus can be categorized into two distinct forms: primary tinnitus, which is idiopathic in nature and may occur with or without concurrent SNHL; and secondary tinnitus, which arises as a consequence of an identifiable underlying medical condition. Several risk factors have been identified in biomedical literature, including aging, medication use, and frequent exposure to loud noise, otological diseases, cardiovascular and cerebrovascular conditions, as well as lifestyle and behavioural factors (Hoffman & Reed, 2004). Additionally, studies have reported a link between tinnitus and psychological conditions such as anxiety and depression (Bhatt et al., 2016; Osterloo et al., 2021 Hackenberg et al., 2023). Emerging research also suggests that central auditory processing abnormalities, neuroplastic changes, and genetic predispositions may contribute to its development (Bashir et al., 2023; De Ridder et al., 2021; Wu et al., 2023)

2.1.3 Psychological and Emotional Impact

Tinnitus can be debilitating when it significantly affects quality of life. Beyond its auditory symptoms, it often imposes a substantial psychological burden. Anxiety, depression,

and sleep disturbances are commonly reported among individuals with tinnitus, alongside difficulties with concentration and attention (Leong et al., 2020). These challenges can interfere with work, social interactions, and leisure activities, disrupting daily routines. While the emotional impact varies from person to person, the bidirectional relationship between tinnitus and psychological well-being underscores the need for a holistic approach to management.

2.2 OHCs and Their Role in Auditory Function

OHCs, situated within the organ of Corti in the cochlea, are essential to the auditory process. The cochlea itself is a fluid-filled, spiral-shaped structure of the inner ear that facilitates the conversion of mechanical sound vibrations into neural signals, enabling auditory perception by the brain (Mahapatra et al., 2025). OHCs significantly contribute to this process by amplifying sound, enhancing auditory sensitivity, and providing essential feedback to inner hair cells (IHCs), which further refine the precision of auditory signals (Sasan et al., 2025). These highly specialized cells are fundamental to refining the auditory system's dynamic range, enabling the perception of low intensity sounds and the precise differentiation of sound frequencies. This function is facilitated by a distinctive mechanism known as electromotility; whereby OHCs undergo changes in length in response to electrical stimuli.

The cochlear amplifier mechanism, involving feedback from OHCs to IHCs, is a fundamental part of this process. This mechanism not only amplifies sound signals by increasing basilar membrane motion but also improves frequency discrimination and auditory precision (Brownell, 2017; Rabbitt & Bidone, 2024). OHCs play a critical role in maintaining the cochlea's tonotopic organization, where different areas of the cochlea are specialized to respond to specific frequencies of sound. This precise mapping of sound frequencies across

the cochlea allows for the perception of a broad range of pitches, which is crucial for understanding speech and music. Additionally, OHCs help protect the cochlea from damage caused by loud noises through a process known as cochlear compression (Rajan, 2001). In this process, OHCs reduce their sensitivity when exposed to loud sounds, effectively preventing overstimulation that could damage the cochlea's structures. This protective mechanism is essential for maintaining hearing health over time, particularly in environments with high levels of noise exposure.

OHCs are also responsible for generating OAEs, which are low-intensity sounds emitted by the cochlea in response to acoustic stimulation. These emissions can be captured in the external ear canal using highly sensitive microphones and serve as a valuable non-invasive diagnostic measure for evaluating cochlear, particularly OHC, function and integrity. OAEs serve as an objective measure of OHC function and are valuable for identifying cochlear dysfunction.

Their relevance has gained particular attention in recent years due to the growing interest in individuals with tinnitus. Research has shown that abnormalities in OAE responses are common among individuals with tinnitus (Cima et al., 2021; Jedrzejczak et al., 2023; Ueberfuhr et al., 2020, Ceranic et al., 1998; Hall, 2000). Additionally, reductions in distortion-product otoacoustic emission (DPOAE) amplitude have been observed in cases of noise-induced tinnitus (Job et al., 2007). These changes in OAE patterns reflect disruptions in cochlear feedback mechanisms and may indicate dysfunction of the OHCs themselves. In some cases, OHC dysfunction can lead to altered neural activity, which has been implicated in the generation of phantom sounds, or tinnitus (Comer, 2023). The presence or absence of OAEs, as well as their amplitude and frequency, can provide valuable insights into cochlear health and the potential causes of tinnitus.

It has been suggested that OAEs are more sensitive indicators of cochlear dysfunction than traditional hearing threshold measurements, such as pure-tone audiometry (PTA) (Marshall et al., 2001). As a result, OAEs have been proposed as a tool for detecting early or preclinical hearing loss, particularly in individuals with 'normal' hearing thresholds (Jedrzejczak et al., 2022). Some studies have shown that individuals with tinnitus, even those with 'normal' hearing, may exhibit abnormal OAE responses, which suggests that cochlear dysfunction could still be present despite 'normal' PTA results (Ozimek et al., 2006; Ami et al., 2008; Fabijańska et al., 2012). Conversely, some tinnitus patients may display enhanced DPOAEs at certain frequencies, further complicating the interpretation of OAE data in tinnitus research (Gouveris et al., 2005; Sztuka et al., 2010). The relationship between OAE abnormalities and tinnitus remains a subject of ongoing investigation, with studies yielding mixed results on the role of cochlear dysfunction in tinnitus generation. Nonetheless, the consistent presence of abnormal OAEs in individuals with tinnitus, even in those within clinically 'normal' hearing thresholds, underscores the importance of including OAE measurements as part of a comprehensive diagnostic approach.

The efferent division of the auditory system, with particular emphasis on the olivocochlear system, serves a critical modulatory function in regulating the activity of OHCs. Arising from the superior olivary complex, the olivocochlear system is anatomically and functionally divided into two principal pathways: the lateral olivocochlear (LOC) and medial olivocochlear (MOC) bundles (LePage, 1989; Novanta et al., 2014). The LOC bundle projects ipsilaterally to IHCs, while the MOC bundle primarily innervates OHCs. The MOC bundle, made up mostly of myelinated fibres, plays a key role in modulating OHC function, particularly in response to noise exposure or electrical stimulation (Groff & Liberman, 2003). Upon activation, the MOC system exerts an inhibitory influence on OHC motility, thereby diminishing the amplitude of OAEs. This regulatory mechanism serves a protective role by

attenuating excessive cochlear amplification, safeguarding the auditory system from overstimulation and potential acoustic injury. Such regulation is vital for preserving auditory sensitivity and ensuring resilience against damaging levels of sound exposure.

Emerging OAE measurement techniques demonstrate significant diagnostic potential for tinnitus by overcoming key limitations of conventional methods. Specifically, high-frequency DPOAEs (HF-DPOAEs), >8 kHz, have proven capable of detecting subtle OHC dysfunction in tinnitus patients who show 'normal' hearing thresholds on standard audiograms, revealing cochlear damage that would otherwise remain undiagnosed (Jedrzejczak et al., 2023). Recent clinical studies using these extended frequency ranges have identified significant OHC abnormalities in 62% of tinnitus cases with clinically 'normal' hearing (Ueberfuhr et al., 2020), suggesting they may serve as sensitive biomarkers for hidden cochlear pathology. Furthermore, innovations in stimulus-frequency OAE (SFOAE) phase-gradient analysis are showing promise for predicting treatment outcomes, with specific OAE patterns correlating with positive responses to neuromodulation therapies (Bashir et al., 2023; Cima et al., 2021). These advances offer clinicians two crucial diagnostic advantages: (1) the ability to objectively confirm cochlear involvement in tinnitus cases where traditional tests prove 'normal', and (2) the capacity to guide personalized treatment selection based on physiological markers rather than subjective reports. While standardization across clinics remains a challenge (Dreisbach & Siegel, 2016), these technological developments are bridging an important gap between phenomenological reports and the underlying pathophysiology of tinnitus.

2.3 Physiological Basis of Tinnitus and OHC Dysfunction

The exact pathophysiological mechanisms underlying tinnitus remain unclear. However, it is now recognized that any pathology capable of affecting the auditory pathways,

whether through peripheral or central mechanisms, can potentially lead to tinnitus. One of the primary contributors to tinnitus is believed to be OHC dysfunction.

Under 'normal' conditions, OHCs generate low intensity sounds that travel in reverse from the OHCs through the perilymph, oval window, middle ear, and finally into the external auditory canal. These sounds, known as OAEs, can be categorized into spontaneous OAEs (SOAEs), SFOAEs, transient-evoked OAEs (TEOAEs), and DPOAEs.

Emerging evidence indicates that OHC dysfunction may play a key role in both the onset and persistence of tinnitus (Shim et al., 2022; Wu et al., 2023). Disruptions in the delicate feedback mechanisms involving OHCs can alter neural activity, potentially leading to the perception of phantom sounds (Bashir et al., 2023; Ueberfuhr et al., 2020).

2.4 Current Theories on the Mechanism of Tinnitus

As previously mentioned, the exact mechanism underlying tinnitus remains unknown, but a widely accepted explanation is that it involves altered neural processing of auditory signals, particularly following damage to hair cells (Haider et al., 2018). Tinnitus is thought to arise from cochlear abnormalities, specifically outer and inner hair cell dysfunction. Damage to these structures, due to various aetiologies, can disrupt the resting activity of afferent auditory nerve fibres, alter neuronal activity in the auditory brainstem, and trigger functional reorganization in higher auditory centres (Makar, 2021). Despite extensive research, there is currently no objective method to detect or quantify tinnitus severity without patient cooperation (Shoushtarian et al., 2020).

Although tinnitus may involve dysfunction across various levels of the auditory pathway, its origin is frequently localized to the cochlea. Jastreboff (1990) posited that the condition commonly initiates within the cochlea, subsequently leading to maladaptive neural

activity in central auditory structures. This aberrant central processing is believed to maintain the chronic perception of tinnitus in the absence of ongoing peripheral input.

Although no single theory fully explains tinnitus, emerging research suggests that maladaptive plasticity, altered neural gain, disrupted sensory gating, and aberrant oscillatory activity contribute to its perception. Ongoing studies continue to refine our understanding, offering potential insights into future diagnostic and therapeutic strategies.

2.4.1 The Neurophysiological Model

The neurophysiological model proposed by Jastreboff and Hazell (1990) proposes that tinnitus arises as a consequence of aberrant neural activity within the central auditory pathways, typically following peripheral auditory damage. This framework further emphasizes the integrative involvement of non-auditory systems, most notably the limbic and autonomic nervous systems, which are believed to modulate the emotional and physiological dimensions of tinnitus perception. According to this model, tinnitus-related distress is determined primarily by these systems. When an abnormal auditory signal is introduced at low levels, subcortical centres enhance it, relay it to the auditory cortex, and ultimately perceive it as tinnitus. Over time, if no strong emotional or behavioural associations develop, the brain may habituate to the tinnitus signal, reducing its perceived impact.

The neurophysiological model of tinnitus, initially proposed by Jastreboff and Hazell (1990), conceptualizes tinnitus as the perception and cognitive interpretation of an abnormal auditory signal originating either from the cochlea or the retrocochlear/central auditory regions. According to this framework, the novel signal is transmitted from the peripheral auditory structures and processed through subcortical and cortical centres, where it acquires perceptual and emotional significance.

Over the years, substantial empirical evidence has reinforced the association between various traumatic insults and cellular injury to both OHCs and IHCs (Baguley, 2002; Sziklai, 2004; Vijayakumar et al., 2022). It has been observed that localized damage to the basilar membrane often results in a patchwork of impaired OHCs adjacent to relatively intact IHCs (Moore, 2001). Due to their anatomical positioning and greater susceptibility, OHCs are typically the first to incur damage and do so more extensively than IHCs (Kemp, 2009).

This differential vulnerability underpins what is known as the discordant damage theory, which posits that partial hair cell loss, particularly of the OHCs, can lead to abnormal afferent signalling at frequencies near the damaged site (Jastreboff, 1990). As both OHCs and IHCs transmit afferent input to the same neural populations within the dorsal cochlear nucleus, selective OHC dysfunction disrupts the balance of excitatory input. When IHCs remain functional while OHCs are impaired, this imbalance generates aberrant neural activity within the central auditory system, manifesting as high-frequency bursts that are perceived as tinnitus.

Notably, Jastreboff (2000) emphasized that even subclinical OHC damage, affecting up to 30% of the OHC population, may not be detectable through conventional PTA, yet still be sufficient to induce tinnitus symptoms.

The neurophysiological model offers a fundamentally different perspective on tinnitus by suggesting it results from the combined activity of several subsystems within the nervous system. In this model, the auditory pathways contribute to the perception of sound, but it is primarily the limbic system that determines the emotional response and perceived distress associated with tinnitus. At lower levels, the auditory system typically generates random, spontaneous neural activity that does not lead to conscious sound perception. However, when external sounds are introduced, this neural activity becomes more synchronized and

organized, leading to sound detection (Møller, 1984; Eggermont, 1990). The brain continuously adjusts its sensitivity to detect changes in this spontaneous activity based on ambient sound levels. For instance, in near-silent environments, individuals may begin to notice subtle bodily sounds or develop the perception of tinnitus. This heightened auditory sensitivity has been observed in animal studies, where induced hearing loss increased neuronal responsiveness in auditory pathways (Jastreboff, 1990; Sasaki et al., 1980; Gerken, 1992, 1993). Tinnitus is thought to occur when spontaneous activity, which is normally filtered out, becomes strong or organized enough to be recognized as sound. This aberrant signal may originate from an imbalance in the activity of type I and type II auditory nerve fibres, often caused by uneven damage to OHCs and IHCs (Jastreboff, 1990; 1995), though other mechanisms could also be involved.

2.4.2 Sensory Deprivation Theory

Tonotopic organization within the auditory system refers to the spatial mapping of sound frequencies, wherein specific regions of the basilar membrane correspond to and project afferent input to distinct locations along the central auditory pathway (Peterson & Hamel, 2023). When cochlear damage occurs, the affected frequency region ceases to transmit sensory input, resulting in a localized loss of afferent stimulation (Shibata et al., 2011). This sensory deprivation is believed to induce functional reorganization within the corresponding areas of the central auditory system. Several researchers have proposed that such deprivation may trigger increased spontaneous neuronal activity and maladaptive plasticity, leading to disordered firing patterns that are interpreted by the brain as tinnitus (Dotan & Shriki, 2021).

Once a signal is perceived, a process of evaluation and comparison of other familiar patterns takes place at the subcortical centre, where unimportant signals are subconsciously selected and filtered out (Jastreboff, 2015). The limbic or autonomic system will not be

stimulated if signals are deemed to be neutral on repetitive application. This is known as habituation. However, if the sound causes stimulation of the autonomic and limbic system with increased awareness and annoyance towards the sound, tinnitus will be viewed as a negative symptom (Henry, 2023). A strong conditioned reflex with negative reinforcement will occur when it comes to tinnitus and the emotional reaction of tinnitus.

In 1983, researchers developed an animal model of tinnitus in which silence was used as a conditioned stimulus to represent tinnitus perception (Jastreboff et al., 1998). This model was instrumental in identifying the patterns of neuronal activity associated with tinnitus. While it has been widely assumed that increased spontaneous firing in the auditory pathways underlies tinnitus perception, studies involving single-neuron recordings in the external and dorsal nuclei of the inferior colliculus in rats presented a more refined picture. The findings revealed that elevated spontaneous activity was associated with hearing loss but did not align with behavioural indicators of tinnitus. Instead, a distinct pattern of bursting, seizure-like neural activity was observed in rats exhibiting behavioural signs of tinnitus; a phenomenon not seen in control animals. This abnormal bursting activity correlated with the presence of tinnitus rather than hearing loss (Chen & Jastreboff, 1995; Kwon et al., 1999).

Previously, tinnitus was assumed to originate solely in the ear, particularly in cases of objective tinnitus, where sound is generated by physiological processes such as blood flow or muscle contractions (Lockwood et al., 2002). Rare instances of spontaneous otoacoustic emissions have also been linked to tinnitus (Penner & Bilger, 1992). However, modern consensus attributes subjective tinnitus to neural generators in the auditory cortex or subcortical auditory nuclei (Eggermont & Roberts, 2012). Current theories, supported by animal and human studies, suggest that tinnitus arises as a compensatory response to reduced sensory input, often referred to as maladaptive plasticity (Shore et al., 2016).

2.4.3 Neuronal Gain Hypothesis

The neuronal gain theory proposes that tinnitus results from increased central auditory gain, in which the brain compensates for reduced auditory input by amplifying neural activity, leading to the perception of sound (Schaette & McAlpine, 2011).

Research in animal models has demonstrated increased spontaneous firing rates (SFR) and heightened neural responsiveness in the cochlear nucleus (CN) following noise trauma (Kaltenbach et al., 2005; Dehmel et al., 2012). This hyperactivity is thought to stem from homeostatic plasticity mechanisms triggered by auditory deprivation. Reduced auditory input leads to a decline in GABAergic inhibition (Middleton et al., 2011) and a decrease in inhibitory glycine receptors (Wang et al., 2009). Additionally, an upregulation of vesicular glutamate transporter has been observed in the CN (Barker et al., 2012), further contributing to hyperactivity.

Hyperactivity extends beyond the cochlear nucleus. Increased SFR has also been recorded in the inferior colliculus (IC) following noise trauma (Berger & Coomber, 2015), though some evidence suggests this activity originates in the CN rather than the IC itself (Manzoor et al., 2013). Similarly, studies on IHC loss following ototoxic exposure show a reduction in compound action potentials from auditory nerve fibres, but only a minor reduction in evoked responses in the IC, suggesting compensatory amplification in central auditory processing (Salvi et al., 2016).

Human neuroimaging studies support these findings. Functional MRI studies indicate increased blood-oxygen-level-dependent responses in the IC (Boyen et al., 2014) and the medial geniculate body (Melcher et al., 2009). However, these changes are also observed in

individuals with hyperacusis, complicating interpretations that isolate tinnitus-related neural activity (Gu, 2011).

Notably, auditory cortex hyperactivity can be reversed through interventions such as vagus nerve stimulation paired with auditory input (Engineer et al., 2011) or GABA-inhibiting drugs (Yang et al., 2011), providing potential avenues for tinnitus treatment.

Despite its utility, the increased gain hypothesis lacks specificity, as neuronal excitability depends on both intrinsic properties and altered synaptic inhibition/excitation balance (Auerbach et al., 2014).

2.4.4 Frontostriatal Gating Hypothesis

An alternative perspective is the frontostriatal gating hypothesis, which suggests that tinnitus perception and distress result from dysregulated sensory gating within the ventromedial prefrontal cortex and nucleus accumbens (Rauschecker, 2024). These regions are involved in filtering irrelevant sensory inputs and assigning emotional significance to stimuli. Disruptions in this network may lead to an inability to suppress tinnitus-related neural activity or an inappropriate emotional response to the sound.

Voxel-based morphometry studies have found reduced grey matter volume in the ventromedial prefrontal cortex of tinnitus patients compared to controls (Mühlau et al., 2006), and fMRI studies reveal hyperactivity in the nucleus accumbens in response to auditory stimuli in individuals with tinnitus (Leaver et al., 2011). The resemblance between tinnitus and chronic pain suggests that both conditions share similar underlying mechanisms involving abnormal sensory gating and heightened distress responses (Rauschecker, 2024). However, it remains unclear whether these changes in brain function cause tinnitus or arise as a consequence of persistent tinnitus perception.

2.4.5 Predictive Coding Hypothesis

The predictive coding model of tinnitus suggests that spontaneous neural activity within the auditory system serves as a tinnitus precursor (Sedley et al., 2016). Normally, top-down predictions from higher auditory centres suppress expected neural noise, maintaining a perception of silence. However, when afferent input is altered (e.g., through increased spontaneous activity or neuronal synchrony), the prediction error threshold may be exceeded, leading to conscious tinnitus perception. Over time, if attention remains focused on the tinnitus signal, it may become the new default auditory perception, reinforced through acetylcholine-mediated neuromodulation and memory structures.

2.4.6 Thalamocortical Dysrhythmia Hypothesis

The thalamocortical dysrhythmia model proposes that tinnitus results from abnormal oscillatory activity in the auditory system. Peripheral auditory damage leads to reduced alpha-band (8-12 Hz) activity, causing a disinhibition of gamma-band (>30 Hz) activity, which has been correlated with tinnitus loudness in EEG and MEG studies (van der Loo et al., 2009; Müller et al., 2013). This model suggests that tinnitus is sustained by abnormal thalamocortical interactions, with increased gamma activity reflecting a maladaptive response to decreased auditory input (De Ridder et al., 2015).

2.4.7 The Discordant Damage Theory & OHC Dysfunction

One hypothesis for tinnitus suggests that it results from disproportionate damage between different types of hair cells in the cochlea. Cochlear damage often results from traumatic events like exposure to loud noise or the administration of ototoxic medications. Such damage commonly originates in the basal turn of the cochlea, which processes high-frequency sounds, and typically impacts the OHCs first, before progressing to the IHCs,

which are affected later (Salvi et al., 2000). As a result, some cochlear regions may experience total loss of both OHCs and IHCs, while others may retain functional IHCs despite damaged OHCs.

Lesions affecting OHCs alter the mechanical properties of the organ of Corti, leading to tonic depolarization of IHCs and irregular activity in afferent auditory fibres (Novanta et al., 2014). When groups of OHCs are damaged, auditory input to the brain is reduced. This reduction in input subsequently lowers efferent feedback and suppresses the rapid contractile function of OHCs within the affected area (Chung & Lee, 2016). Given the diffuse nature of efferent fibre innervation, this inhibition can impact adjacent healthy regions, potentially triggering hyperactivity in nearby functional OHCs (Sturm & Weisz, 2015). This increased neural activity may be perceived as tinnitus.

Granjeiro (2012) proposed that reduced efferent inhibition in tinnitus patients may stem from functional characteristics of the efferent system, originating in the cochlea or the MOC system. This dysfunction could be linked to the activation of the MOC system or a combination of multiple factors. Furthermore, the medial efferent system, modulated by the autonomic nervous system, may play a role in the variability of tinnitus symptoms during periods of stress. This indicates a potential link between parasympathetic activity and efferent disinhibition.

Jastreboff (2004) further described a possible explanation for tinnitus in individuals with within ‘normal’ hearing. According to this theory, damage to a limited area of OHCs, undetectable in conventional audiograms when IHCs remain intact, can create an imbalance in neural activity between Type I and Type II auditory nerve fibres. This imbalance, when amplified through different levels of the auditory pathway, may ultimately be perceived as tinnitus.

OHC dysfunction can manifest in various ways and is commonly linked to auditory changes. It may lead to reduced hearing sensitivity, particularly for soft or low-intensity sounds. Since OHCs play a key role in frequency discrimination, their dysfunction can impair the ability to distinguish between different pitches. Additionally, OHC impairment often results in altered or absent OAEs, which are routinely assessed in clinical evaluations of cochlear function (Kemp, 2002). Notably, OHC dysfunction has been closely associated with tinnitus, even in individuals with hearing within clinically 'normal' hearing thresholds, suggesting that changes in OHC activity may contribute to its perception (Novanta, 2014).

Since OHCs generate OAEs these emissions serve as a valuable clinical tool for assessing OHC function. OAEs are commonly used in hearing screening programs to detect early signs of cochlear dysfunction (Hunter, 2020), further emphasizing the critical role of OHCs in auditory health.

2.5 Tinnitus and within 'normal' hearing thresholds: A complex interaction

Tinnitus is a hyperactive auditory system activity and is considered one of the most complex conditions affecting the hearing system, with a prevalence of approximately 1-14% in the general population (Jarach et al., 2022). Among individuals who report tinnitus, 8-10% do so despite having 'normal' audiometric hearing thresholds (Sanchez et al., 2005).

The coexistence of tinnitus and 'normal' hearing challenges the traditional view that tinnitus is exclusively linked to measurable auditory damage. Studies have consistently identified a subgroup of individuals with tinnitus whose audiometric thresholds fall within the clinically 'normal' range (Mckee & Stephans, 1992; Zhao et al., 2014; Xiong et al., 2019; Kara et al., 2020).

Although cochlear damage is typically associated with elevated hearing thresholds, the absence of detectable hearing loss does not necessarily rule out cochlear dysfunction

(Liberman et al., 2016). The role of cochlear function in tinnitus perception is increasingly recognised, and objective, non-invasive methods such as DPOAEs and TEOAEs provide valuable tools for detecting subtle cochlear abnormalities (Ishak et al., 2013).

A deeper exploration of the literature reveals that HF-DPOAEs and extended high-frequency (EHF) audiometry are increasingly recognized as valuable tools for detecting subtle cochlear dysfunction in tinnitus patients, particularly those with conventional audiograms. Several studies have demonstrated that tinnitus patients often show poorer EHF thresholds and more frequent DPOAE abnormalities compared to controls, suggesting the presence of subclinical cochlear damage that is not captured by standard hearing tests (Fabijańska et al., 2012; Onishi et al., 2004).

Hidden hearing loss (HHL) refers to a deficit in auditory perception that is not detectable through standard PTA, which measures hearing sensitivity. Unlike conventional hearing loss, where thresholds are elevated, individuals with HHL often exhibit 'normal' audiograms but struggle with speech comprehension in noisy environments, suggesting deficits in auditory processing (Kobel et al., 2017). Recent research has investigated possible mechanisms contributing to HHL, such as cochlear synaptopathy, referring to the loss of synaptic connections between IHCs and auditory nerve fibres, and neural degeneration within the auditory pathway (Liberman & Kujawa, 2017).

Additionally, there is growing interest in the relationship between HHL and tinnitus, a phantom auditory perception often associated with hearing damage. This literature review examines the current understanding of these connections.

2.5.1 Hidden Hearing Loss: Mechanisms and Diagnosis

The primary proposed mechanism of HHL is cochlear synaptopathy, where noise exposure or aging leads to the degeneration of synapses between IHCs and auditory nerve

fibres, particularly those with high thresholds (low-spontaneous-rate fibres) (Liberman & Kujawa, 2017). This damage does not immediately affect hearing thresholds but impairs temporal processing and signal-in-noise detection (Bharadwaj et al., 2014). Studies using electrophysiological measures, such as auditory brainstem responses (ABRs), have shown reduced wave I amplitudes in individuals with suspected HHL, supporting the synaptopathy hypothesis (Bramhall et al., 2019).

Behavioural tests, such as speech-in-noise perception tasks and gap detection tests, have also been used to identify HHL (Plack et al., 2014). However, diagnosing HHL remains challenging due to the lack of a standardized clinical test, leading to ongoing debate about its prevalence and significance (Le Prell & Clavier, 2017).

2.5.2 Hidden Hearing Loss and Tinnitus: A possible Connection

Tinnitus is commonly associated with hearing loss, but some individuals with 'normal' audiograms also experience tinnitus, raising questions about underlying mechanisms (Eggermont & Roberts, 2015). One hypothesis is that cochlear synaptopathy, a hallmark of HHL, may contribute to tinnitus by disrupting neural signalling and inducing maladaptive plasticity in the central auditory system (Schaette & McAlpine, 2011).

Research indicates that decreased input from the auditory nerve, resulting from synaptopathy, may trigger hyperactivity in the central auditory pathway as a compensatory response to reduced peripheral stimulation (Gu et al., 2010). This neural hyperactivity could manifest as tinnitus (Shore et al., 2016). Animal studies have shown that noise exposure causing synaptopathy can lead to tinnitus-like behaviour even without threshold shifts (Hickox & Liberman, 2014). Similarly, human studies have found correlations between tinnitus and deficits in temporal processing, a feature of HHL (Weisz et al., 2006).

However, the relationship between HHL and tinnitus remains inconclusive. Some individuals with HHL do not develop tinnitus, while others with tinnitus show no clear evidence of synaptopathy (Guest et al., 2017). This suggests that additional factors, such as genetic predisposition, stress, or central gain mechanisms, may modulate the tinnitus percept (Sedley et al., 2016).

For example, Fabijańska et al. (2012) found that subjects with unilateral tinnitus and within 'normal' hearing thresholds within the conventional frequency range exhibited significantly higher EHF thresholds and lower DPOAE levels than controls, especially at 2 kHz and 8 kHz. These findings imply that cochlear impairment in the basal region, often not assessed by standard audiometry, may contribute to tinnitus perception. The study also highlighted that DPOAE levels in tinnitus ears were generally lower than in non-tinnitus ears, indicating that DPOAEs can reveal subclinical outer hair cell dysfunction that may underlie tinnitus even when pure-tone thresholds remain 'normal'.

Onishi et al. (2004) further supported the clinical relevance of DPOAEs, reporting a higher prevalence of DPOAE alterations among tinnitus patients with 'normal' audiograms (18.8%) and those with SNHL (61.3%), compared to controls (3.6%). The authors concluded that while not all tinnitus patients show DPOAE abnormalities, the presence of such alterations is correlated with tinnitus complaints, reinforcing the utility of DPOAEs as an objective measure in tinnitus evaluation.

Clinical case reports and guidelines also emphasize the sensitivity of DPOAEs to early cochlear damage. For instance, DPOAEs have detected early signs of ototoxicity or cochlear dysfunction in patients with 'normal' audiograms, as seen in cases of chemotherapy-induced hearing changes or diabetes-related cochlear compromise (Rupa, 2002). Moreover, DPOAEs have been included in clinical protocols for ototoxicity monitoring and are

recommended for screening at-risk populations, such as industrial workers and military personnel (British Society of Audiology, 2023).

The integration of DPOAEs and EHF audiometry into clinical practice has several implications (BSA, 2023; Rupa, 2002):

- Early Detection: These measures can identify cochlear dysfunction before it manifests as a threshold shift on standard audiograms, allowing for earlier intervention and monitoring in at-risk individuals.
- Objective Assessment: DPOAEs provide an objective, non-invasive method to assess cochlear status, which is particularly valuable in the evaluation of subjective symptoms like tinnitus.
- Tailored Management: Detecting subclinical damage can inform counselling, preventive strategies, and personalized management plans for tinnitus patients, even when traditional audiometry appears ‘normal’.
- Monitoring Progression: Repeated DPOAE and EHF assessments can track cochlear changes over time, supporting decisions about ototoxic medication use or noise exposure management.

However, it is important to recognize the limitations. Not all tinnitus patients exhibit DPOAE abnormalities, and the relationship between DPOAEs, tinnitus, and hearing thresholds is influenced by factors such as middle ear status and the specific site of auditory dysfunction (Kramer, 2013; Dhar & Hall, 2018; BSA, 2023). Thus, DPOAEs should be interpreted as part of a comprehensive test battery rather than as a standalone diagnostic tool.

This discrepancy highlights the need for a more in-depth understanding of the mechanisms contributing to tinnitus in individuals with 'normal' hearing. Further research is essential to unravel the complexities of tinnitus beyond conventional audiometric measures.

In summary, the literature supports the clinical value of HF-DPOAEs and EHF audiometry in revealing hidden cochlear deficits in tinnitus patients, guiding early detection, objective assessment, and individualized management. Their routine use in tinnitus clinics could enhance diagnostic accuracy and patient care, particularly for those with 'normal' conventional audiograms but persistent auditory complaints.

2.6 OAE Findings in Tinnitus: Contraindications, Mechanisms and Unresolved Questions

The relationship between tinnitus perception and OAEs remains one of the most debated topics in auditory neuroscience. While OAEs, particularly DPOAEs, are widely used to assess cochlear OHC function in tinnitus patients; the literature reveals striking contradictions. Several studies have shown abnormal OAE findings in this population (Fabijanska et al., 2012; Granjeiro et al., 2008; Hall, 2000; Zhao et al., 2014; Yenigun et al., 2014; Modh et al., 2014; Mokrian et al., 2014). Some studies report reduced or absent OAEs at frequencies corresponding to tinnitus pitch (Bartnik et al., 2004; Hall, 2000; Satar et al., 2003), suggesting OHC dysfunction as a key driver. Others, however, find this correlation inconsistent (Shekhawat et al., 2014) or even report elevated OAEs in tinnitus patients (Sztuka et al., 2010). These discrepancies appear to reflect more than just random variation; they reflect fundamental differences in study design, patient populations, and underlying pathophysiological mechanisms. A deeper examination reveals that the OHC-tinnitus link is not uniform but rather a spectrum of dysfunction, compensatory plasticity, and efferent modulation, each contributing to the heterogeneity of findings.

2.6.1 The OAE-Tinnitus Correlation: Evidence for OHC Dysfunction

A significant body of research supports the idea that tinnitus is associated with reduced OAE amplitudes, indicative of OHC damage or impaired cochlear amplification. Modh et al. (2014) and Mosh et al. (2014), for example, found significantly lower DPOAE amplitudes across tested frequencies (750-8000 Hz) in individuals with tinnitus having within 'normal' hearing thresholds compared to controls. These results align with earlier work by Shiomi et al. (1997), who observed substantial DPOAE reductions at 4-7 kHz in the tinnitus group, and Dall'Igna et al. (2015), who reported absent or reduced DPOAEs in 60% of tinnitus patients with clinically 'normal' hearing. Such findings imply that even in the absence of audiometric hearing loss, subtle OHC dysfunction, detectable only through OAEs, may contribute to tinnitus generation. More recent studies by Ami et al. (2024), Emadi et al. (2024), Abo Jamous et al. (2024), and others, have consistently reported reduced DPOAE amplitudes in tinnitus patients across a broad frequency range, supporting the notion that OHC dysfunction is implicated in tinnitus development.

The clinical implications are profound. If OAEs can objectively identify cochlear dysfunction in tinnitus patients with 'normal' audiograms, they could serve as an early diagnostic tool, bridging the gap between subjective tinnitus complaints and measurable pathology. This is particularly relevant for cases of HHL, where synaptic damage or OHC impairment precedes threshold shifts (Kara et al., 2020). The frequency specificity of OAEs further enhances their utility, allowing clinicians to pinpoint cochlear regions that may correspond to tinnitus perception. For instance, Lui et al. (unpublished, cited in Shore et al., 2016) noted that 59% of tinnitus patients exhibited reduced DPOAEs at their tinnitus-matched frequencies but had clinically acceptable responses elsewhere, suggesting localized OHC dysfunction rather than global cochlear decline.

However, the correlation between tinnitus pitch and OAE abnormalities is not absolute. Shekhawat et al. (2014) demonstrated that self-reported tinnitus pitch often misaligns with OAE dip locations, raising questions about the reliability of pitch matching as a diagnostic tool. This inconsistency may stem from central auditory reorganization, where tinnitus-related neural activity shifts tonotopically over time, decoupling it from its original cochlear origin. Alternatively, methodological differences, such as variations in OAE stimulus levels or frequency resolution, could obscure true effects. For example, some studies use fixed stimulus levels, while others employ individualized levels based on hearing thresholds, potentially altering OAE sensitivity to subtle OHC damage.

2.6.2 The Paradox of Elevated OAEs in Tinnitus: Evidence for Compensatory Hyperactivity

In stark contrast to studies reporting OAE reductions, Sztuka et al. (2010) documented significantly larger DPOAE amplitudes at 3003, 4004, and 5005 Hz in tinnitus patients compared to controls. This counterintuitive finding challenges the prevailing OHC-dysfunction model and instead suggests that tinnitus may arise from OHC hyperactivity, possibly due to decreased efferent inhibition. The MOC system, which normally suppresses OHC motility, could become hypoactive in tinnitus, releasing OHCs from inhibitory control and enhancing cochlear amplification. This aligns with Gouveris et al. (2005), who observed higher DPOAE amplitudes at high frequencies (4-6.3 kHz) in tinnitus patients, alongside reduced amplitudes at mid-frequencies (1650-2400 Hz), this bidirectional pattern implicated efferent dysregulation.

The hyperactivity hypothesis gains further support from animal models. Following noise exposure, some studies report temporary OHC gain increases as a compensatory response to peripheral damage (Rajan, 2001). If sustained, this could manifest as elevated OAEs and contribute to tinnitus by over amplifying spontaneous neural activity. However,

human data remain conflicting. While Sztuka et al. (2010) and Gouveris et al. (2005) found evidence of OHC hyperactivity, others, such as Modh et al., 2014, report only OHC deficits. This discrepancy may reflect differences in tinnitus chronicity: early-stage tinnitus could involve compensatory OHC hyperactivity, whereas chronic cases progress to OHC degeneration. Alternatively, efferent function might vary across individuals, with some exhibiting MOC hypoactivity (leading to OHC hyperactivity) and others showing MOC hyperactivity (causing OHC suppression).

2.6.3 Methodological Divergences: Why Studies Disagree

The conflicting OAE findings in tinnitus research cannot be fully explained by biological variability alone; methodological differences play a significant role. One major issue is the lack of standardization in defining 'normal' hearing. Some studies such as Guest et al. (2017), use strict thresholds (≤15 dB HL), while others such as Fabijanska et al. (2012), permit thresholds up to 25 dB HL, potentially including subjects with mild hearing loss. This is critical because even slight threshold elevations can confound OAE interpretations, as DPOAEs are sensitive to cochlear health well before audiometric changes emerge (Marshall et al., 2001).

Another key variable is the frequency range tested. Most studies focus on conventional audiometric frequencies (0.5-8 kHz), but emerging evidence suggests that high frequency OAEs (up to 16 kHz) may better capture early cochlear damage (Jedrzejczak et al., 2022). For instance, Wiktor Jedrzejczak et al. (2022) found that DPOAE amplitudes at 10-16 kHz were more strongly associated with noise exposure history than standard frequencies, yet few tinnitus studies include this range. This oversight could miss subclinical OHC dysfunction in regions beyond standard audiometry.

Efferent testing protocols also vary widely. Some studies measure contralateral suppression of OAEs to assess MOC function (Granjeiro et al., 2008), while others omit efferent assessments entirely. This is a critical gap, given that efferent modulation could explain why some tinnitus patients show elevated OAEs (reduced suppression) and others show reduced OAEs (excessive suppression). Without standardized efferent testing, comparisons across studies remain fraught.

2.6.4 Toward a Unifying Framework: Integrating OHC Dysfunction and Hyperactivity

The OHC-tinnitus relationship likely exists on a continuum, with both dysfunction and hyperactivity playing roles at different stages or in different subtypes. The discordant damage theory (Jastreboff, 1990) provides one unifying lens: partial OHC loss (undetectable on audiograms) may disrupt the balance between OHC and IHC activity, leading to aberrant neural firing. Early in tinnitus, surviving OHCs could compensate by increasing gain (explaining elevated OAEs), but chronic damage may eventually overwhelm this plasticity, resulting in OHC failure (reduced OAEs).

Efferent feedback further modulates this process. A hypoactive MOC system might initially increase OHC gain, but prolonged disinhibition could exhaust OHC metabolic reserves, hastening dysfunction (Guinan, 2018; Lopez-Poveda, 2018). Conversely, excessive MOC activity, possibly due to stress or noise exposure, could suppress OHCs excessively, reducing OAEs and depriving the auditory system of necessary amplification (Boothalingam & Purcell, 2022).

The OAE-tinnitus literature is marked by contradictions, but these reflect the complexity of tinnitus pathophysiology rather than mere inconsistency. Reduced OAEs dominate the literature, supporting OHC dysfunction as a key mechanism, but elevated OAEs in some studies suggest compensatory plasticity or efferent dysregulation. Methodological

differences, in hearing thresholds, frequency ranges, and efferent assessments, further complicate interpretations. Moving forward, a multimodal, longitudinal approach will be essential to unravel how OHC changes initiate and sustain tinnitus, paving the way for personalized diagnostics and therapies.

2.7 OAEs and Treatment for Tinnitus

There are a few studies on OAE changes associated with the treatment of tinnitus. Successful tinnitus management strategies largely focus on altering the representation of tinnitus in the central nervous system, rather than addressing the cochlear origin of tinnitus (Tass et al., 2012; Eggermont & Roberts, 2012; Langguth et al., 2019; Lefaucheur et al., 2020). This approach stems from the fact that central nervous system plasticity offers greater potential for treatment-induced changes, while peripheral function in the cochlea has limited opportunities for improvement, even with intensive therapy.

2.8 Research Questions

OHCs are central to cochlear function, enabling sound amplification, frequency discrimination, and cochlear protection. Their role in generating OAEs makes them invaluable for assessing cochlear health, especially in tinnitus patients. While OHC dysfunction is implicated in tinnitus, the precise mechanisms remain unclear, and OAE abnormalities offer critical insights into cochlear pathology.

This study addresses the following unresolved questions:

1. Do HF-DPOAE amplitudes differ significantly between individuals with tinnitus and those without, despite clinically ‘normal’ pure-tone audiograms?
2. Is there a correlation between reduced DPOAE amplitudes and the impact of subjective tinnitus?

3. Can HF-DPOAEs (>8000 Hz) reliably differentiate between tinnitus and non-tinnitus individuals?
4. Are specific characteristics of tinnitus, such as sound quality, laterality, and constancy, associated with distinct DPOAE profiles?
5. Is there a difference in DPOAE amplitudes between tinnitus and non-tinnitus individuals with a history of recreational noise exposure?
6. What role do age-related changes play in the interpretation of DPOAE profiles in adults with tinnitus?

By clarifying these relationships, this work aims to advance OAE-based diagnostics and disentangle tinnitus mechanisms from generic hearing loss.

2.9 Conclusion

This chapter has synthesized current evidence on the relationship between cochlear function, OHC dysfunction, and tinnitus, with a particular focus on the diagnostic utility of OAEs. By reviewing conflicting findings and unresolved questions, such as the role of HF-DPOAEs in individuals with tinnitus and 'normal' audiograms, it underscores the need for further empirical investigation.

The following Methodology chapter will detail the experimental design, participant selection criteria, and OAE measurement protocols employed in this study, ensuring rigorous evaluation of cochlear dysfunction in tinnitus. This systematic approach aims to clarify the interplay between OHC activity, OAEs, and tinnitus perception, addressing gaps identified in the literature.

Chapter 3: Methodology

This chapter outlines the methodological framework employed in this study. It presents the research design, participant selection criteria, data collection procedures, ethical considerations, and the approach to data analysis. The study aimed to examine outer hair cell (OHC) function in individuals with tinnitus and clinically 'normal' hearing thresholds using high-frequency distortion product otoacoustic emissions (HF-DPOAEs).

3.1 Research Design

While DPOAEs have been widely used to assess OHC function in hearing loss, there is a notable gap in research applying DPOAEs to evaluate OHC damage in individuals with within 'normal' hearing thresholds and tinnitus. The lack of studies in this specific population underscores the need for further investigation, which is the driving force behind the present study. This study design incorporates a quantitative design, which is commonly associated with the positivist/ post- positivist paradigm; a deductive approach in which a theory is first developed and then tested. The main aim of quantitative health research involves the discovery of relationships between variables and thus is able to discern patterns or trends in the topic under investigation (Pyo et al., 2023). Quantitative research approach involves a methodical investigation that relies on statistical, mathematical, or computational techniques to collect and analyse numerical data (Creswell, 2014). One of the primary features of this type of research is its ability to present findings numerically, aiding in objective interpretation and analysis (Babbie, 2020). The standardised protocols and rigorous statistical analysis aim to ascertain causality, quantify relationships, and generalise results to wider populations (Bryman, 2016). Given the quantitative nature of the study and its specific aims and objectives, a quantitative research approach is well-suited for investigating the link between OAE measurements and tinnitus in adults with 'normal' hearing thresholds.

To strengthen the validity of the findings, a multi-measure quantitative approach was employed for data collection and analysis. The study employed a brief case history, a scaled self- reporting questionnaire, and a series of clinical audiological tests to evaluate the relationship between tinnitus in individuals with 'normal' hearing thresholds in relation to OHC function.

Structured observations and surveys are commonly utilised to gather numerical data, which can then be subjected to statistical analysis to draw objective conclusions (Punch, 2013).

One of the key strengths of quantitative research lies in its ability to produce objective and generalizable findings (Johnson & Christensen, 2017). By employing rigorous statistical techniques, researchers can test hypotheses rigorously and draw conclusions that have broader applicability beyond the specific context of the study (Cohen et al., 2018), whilst also ensuring replicability and objectivity (Muijs, 2010). Additionally, quantitative research allows researchers to use descriptive statistics to summarise the characteristics of the data and inferential statistics to make inferences or predictions about a population based on sample data (Field, 2018). One is able identify correlations and establish causal relationships between variables, though it is important to note that correlation does not imply causation, and causal relationships must be interpreted cautiously (Ary et al., 2019).

Philosophical presumptions, though often implicit (Slife & Williams, 1995), play a significant role in influencing research practice and methodology. These beliefs, which are shaped by disciplinary norms, research communities, advisors, mentors, and past experiences, can lead researchers to embrace qualitative, quantitative, or mixed methods approaches in their research endeavours (Creswell & Plano Clark, 2018). The post-positivist paradigm, closely aligned with quantitative research, questions the notion of absolute truth, and emphasises the

importance of empirical testing of theories through systematic experimentation (Phillips & Burbules, 2000).

The described research study adopted a post-positivist approach, relying solely on quantitative methods for data collection and analysis. This approach emphasises the importance of empirical evidence, objectivity, and statistical significance in the interpretation of findings. Ethical considerations are approached from a standpoint that ensures the validity and reliability of the research findings (Creswell & Creswell, 2018).

Post-positivism represents the thinking after positivism, which questions the conventional wisdom regarding the absolute truth of knowledge (Phillips & Burbules, 2000) and acknowledges that it is impossible to be completely certain of what we know about human behaviour and action (Ryan, 2006). Post-positivists subscribe to a deterministic theory in which causes most likely dictate effects or outcomes (Creswell & Creswell, 2018). As a result, post- positivists' research reflects the necessity of determining and evaluating the factors that influence results, such as those discovered in experiments (Mertens, 2015). Therefore, for a post-positivist, creating numerical measures of observations and examining people's behaviour becomes crucial. Ultimately, to comprehend the world, the laws and theories that govern it must be put to the test, verified, and be refined (Trochim et al., 2016). Therefore, in the a post positivist research methodology, implies that a researcher starts with a theoretical framework, gathers evidence that either confirms or contradicts the theory, makes the necessary adjustments, and carries out additional experiments to test hypotheses (Neuman, 2014; Park et al., 2020).

The post-positivist worldview shapes the research approach in several keyways. Firstly, it guides the formulation of research questions that are amenable to quantitative investigation, such as whether there are differences in OAEs between individuals with tinnitus and ‘normal’

hearing thresholds compared to those without tinnitus and 'normal' hearing thresholds. By focusing on measurable variables and quantifiable outcomes, the study aims to establish empirical relationships between tinnitus, cochlear function, and OAEs.

Additionally, the post-positivist worldview influences the interpretation of findings, prioritising statistical significance and empirical support for hypotheses (Johnson & Onwuegbuzie, 2004). By relying on quantitative data alone, the study aims to provide objective evidence regarding the relationship variables, without subjective interpretation or bias. Quantitative methods were used extensively throughout the research process, including descriptive and correlational analyses, to explore relationships between variables and distinguish patterns in the data (Rana et al., 2021).

The post-positivist perspective informs the selection of methodology, emphasising the use of standardised protocols and quantitative measures to ensure replicability and objectivity (Babbie, 2016). In this case, the study employed DPOAEs measured at multiple frequencies to assess OHC function, along with HF- DPOAEs to explore cochlear health in regions associated with tinnitus perception.

3.2 Participants

This study included two distinct groups: a tinnitus group and a control group. The tinnitus group consisted of adults who experience subjective tinnitus (i.e., ringing, buzzing, or other auditory sounds in the absence of external stimuli) but who had within 'normal' hearing thresholds (≤20dB HL) as determined by pure-tone audiometry (PTA). The control group consisted of adults with no history of tinnitus and within 'normal' hearing thresholds (≤20dB HL). The study focused on individuals aged 18 to 40 years. This age range was selected because it reduced the potential confounding effect of age-related hearing loss and anatomical changes to the inner ear, which is more commonly observed in individuals over the age of 40

(Gates and Mills, 2005; Yamasoba et al., 2013). By limiting the sample to younger adults, the study minimised the risk of age-related variability in hearing sensitivity, ensuring that any differences observed between the tinnitus and control groups are not simply due to 'normal' aging processes.

3.2.1 Inclusion Criteria

Participants in the tinnitus group reported experiencing tinnitus for a minimum duration of three months. This criterion ensured that only individuals with persistent tinnitus are included, as transient tinnitus may not reflect the same underlying pathophysiological mechanisms. In addition, participants in both groups demonstrated 'normal' hearing thresholds, which was assessed using PTA. Specifically, participants required to have hearing thresholds of ≤ 20 dB HL across the frequency range from 250 Hz to 8 kHz. 'Normal' hearing thresholds ensured that any differences in HF-DPOAE results were not attributable to hearing loss but may instead be related to the presence of tinnitus itself (Jedrzejczak et al., 2022).

Inclusion criteria required all participants to demonstrate Type A tympanometry results, indicating 'normal' middle ear status. Hence indicating that the participant did not present with middle ear abnormalities, such as cerumen, present fluid, or Eustachian tube dysfunction, which could confound the results of otoacoustic emission (OAE) testing. This precaution eliminated the possibility that middle ear pathology is influencing DPOAE outcomes (Campos et al., 2016). This makes it possible to assess cochlear function specifically, without interference from outer or middle ear factors.

3.2.2 Exclusion Criteria

Participants were excluded from the study if they exhibit any of the following conditions. Individuals with hearing loss > 20 dB HL at any frequency point on PTA were excluded, as the study's focus was on individuals with 'normal' hearing.

Hearing loss, whether conductive or sensorineural, would likely interfere with DPOAE results and confound the study's ability to assess cochlear function accurately. Additionally, participants with middle ear pathology, including Type B or Type C tympanograms, were excluded. Individuals with neurological disorders were also be excluded, as such conditions may affect the auditory processing, leading to potential confounding in the DPOAE results.

Further exclusion criteria included participants with a history of occupational noise exposure, individuals who were taking ototoxic medications, or those with a history of ear surgery. These factors can have long-lasting effects on hearing and cochlear function, potentially influencing DPOAE results.

While a sample size calculation based on a 95% confidence level and a 5% margin of error would typically be used to estimate population parameters, such as the prevalence of tinnitus within a general population, this approach was not appropriate for the present study. Instead, the focus was on detecting differences between two groups (i.e. tinnitus group and control group). Therefore, a power analysis was conducted to determine the minimum sample size needed to detect statistically meaningful effects between groups.

A power analysis was conducted assuming a medium effect size (Cohen's $d = 0.5$), a significance level of 0.05 (equivalent to a 95% confidence level), and a statistical power of 0.80. The minimum required sample size was 31 participants per group. This approach ensures adequate sensitivity for hypothesis testing while remaining appropriate for the study's scope

and the relatively specific target population- individuals in Malta with tinnitus and 'normal' hearing thresholds.

Participants required to fit into the chosen inclusion criteria in order to participate in the study in the tinnitus group. The same number of participants were needed for the control group. There was a total of 40 participants in this study, 25 (14 males, 11 females) in the tinnitus group and 15 females in the control group. Due to limitations in participant recruitment, the final sample size of the tinnitus and control groups was smaller than anticipated and exhibited uneven group composition.

The age of participants ranged from 19 to 40 years (M = 28.08, SD = 5.92). Age was non-normally distributed, with 70% of participants between 20 and 30 years. The distribution showed moderate positive skewness (0.92) and slight kurtosis (-0.27).

3.3 Recruitment Process

Participants were recruited through a private audiology clinic seeking tinnitus consultation. If the participant fitted into the research inclusion criteria, they were asked whether they wish to participate in the study through an intermediary. The intermediary provided potential participants with an information letter (See Appendix A and B). Those who are interested in participating were then give the researcher's contact details. Upon meeting the researcher, the consent form (see Appendix C and D) was signed.

Convenience sampling is a non-probability sampling technique widely used in research, particularly in fields where access to participants is relatively straightforward (Mweshi et al., 2020). This method involves selecting individuals who are readily available and accessible to the researcher, often based on their proximity or convenience. Unlike probability sampling methods, convenience sampling does not ensure that every member of the population has an

equal chance of being selected, thus limiting its generalisability to the broader population (Edgar & Manz, 2017).

One of the primary advantages of convenience sampling is its ease of implementation. This can save time and resources, making convenience sampling a practical choice for studies with limited budgets or time constraints (Golzar et al., 2022). Additionally, convenience sampling can be particularly useful in exploratory research or when preliminary data is needed to inform future studies (Sedgwick, 2013). By leveraging existing resources and opportunities, researchers can gather valuable insights without extensive planning or recruitment efforts.

A call for participants advert was posted on the 'Department of Human Communication and Disorders' social media page (see Appendix E), as another sampling method. Voluntary response sampling is a non-probability sampling technique where participants self-select to be part of a study (Murairwa, 2015). Instead of the researcher actively recruiting participants, individuals voluntarily choose to participate based on their interest or willingness. This method is commonly used in surveys, online polls, and feedback forms where respondents opt to provide their input.

One of the primary advantages of voluntary response sampling is its simplicity and cost-effectiveness. Researchers can quickly reach a large number of participants without the need for extensive recruitment efforts or resources. Additionally, voluntary response sampling can be useful for capturing the opinions and perspectives of individuals who are highly motivated or have strong opinions on the topic being studied (Murairwa, 2015).

However, these sampling methods also come with several limitations that researchers must consider. Perhaps the most significant drawback is its potential for selection bias. Participants might be likely to have specific characteristics that might motivate their participation. Since participants are not randomly selected from the population, the sample may not be

representative of the target population, leading to skewed or inaccurate results (Shringarpure & Xing, 2014). The lack of randomisation makes it difficult to control for confounding variables and establish casual relationships. Whilst the lack of representativeness undermines the external validity of the study, making it challenging to generalise findings beyond the sampled population. Furthermore, convenience sampling may result in sampling errors, as certain segments of the population may be overrepresented or underrepresented in the sample (Galloway, 2005). This can distort the findings and compromise the validity of any conclusions drawn from the data. Researchers must be mindful of these limitations and acknowledge the potential biases inherent in convenience sampling when interpreting the results.

While convenience sampling facilitated efficient data collection, this approach may limit generalizability due to potential self-selection bias. Future studies should employ stratified sampling to ensure representation across tinnitus severities and aetiologies. Nevertheless, strict inclusion criteria (‘normal’ audiograms, Type A tympanograms) helped control for confounding variables within the current sample.

3.4 Ethical Considerations

Letters requesting permission were sent out to all relevant entities (see Appendix F) Permission was obtained from the lead audiologist of a private audiology clinic (see Appendix G) to recruit participants and conduct clinical tests and questionnaires at their facility. Additionally, participants were recruited through social media advertisements on the ‘Human Communication Sciences and Disorders at UM’ Facebook page (see Appendix H).

All identifying information was removed from collected data to ensure participant anonymity. Ethical approval was sought and obtained from the Faculty Research Ethics Committee (FREC) at the University of Malta (Reference: FHS-2024-00221) (see Appendix

I). Written informed consent was obtained from all participants prior to their involvement in the study.

Recruitment Process:

- Eligible participants were identified through:
    - Referrals from the private audiology clinic (via the clinic's audiologist).
    - Self-referrals via social media campaign.
- Permission was then sought directly from individuals, with no intermediary retaining identifiable data.

3.5 Procedure

3.5.1 Participant Appointment and Consent

All participants whether recruited through the intermediary or self-referred from the social media advertisement who contacted the researcher directly if they wished to participate in the study. The researcher then scheduled an appointment with the participant for testing.

Upon arrival at the clinic, participants were greeted by the researcher. They were provided with the information letter and had the opportunity to ask questions regarding the study's procedures. After sufficient explanation, participants were asked to sign the informed consent form if they agree to partake in the study. Subjects were informed that they may choose to discontinue testing at any given time without giving any reason. A detailed explanation of the testing procedure is described below. The tests took approximately 40 minutes to complete.

3.5.2 Otoscopy

Otoscopy was conducted to inspect the external auditory canal and tympanic membrane for any obstructions such as cerumen or signs of infection that could interfere with tympanometry or OAE testing (Falkson & Tadi, 2020). Otoscopy was performed using an otoscope to visually inspect both ears. Any participants found to have signs of occlusion or infection were excluded from the study.

3.5.3 Tympanometry

Tympanometry was performed on both ears of each participant using a calibrated 'Inventis Flute Diagnostic Tympanometer'. The purpose of tympanometry was to evaluate the middle ear function and ensure a Type A tympanogram was present.

3.5.4 Tinnitus Case History

A brief self- devised case history, provided in English or Maltese (see Appendix J and K respectively) depending on the participant's preference, was taken to gather information on the participant's self- perceived tinnitus characteristics, including:

- Onset and duration of tinnitus
- Frequency and nature of the tinnitus hence referring to continuous as opposed to intermittent and laterality.
- Any potential triggering factors such as noise exposure or medications

3.5.5 4C Tinnitus Management Questionnaire (4C-TQ)

The 4C-TQ (see Appendix L) was administered to participants with tinnitus to assess the severity of their tinnitus. The 4C-TQ measures tinnitus across four domains:

- Cognitive interference (e.g., difficulty concentrating)
- Emotional distress (e.g., anxiety, frustration)

- Behavioural effects (e.g., avoidance of certain environments)
- Severity (e.g., loudness and disturbance caused by tinnitus)

The researcher administered the questionnaire verbally, and scores were entered via Google Form. The total 4C score was derived using a validated calculation method that produces a percentage-based index of tinnitus management confidence. Each item is rated on a scale from 0 to 10, where 0 indicates no confidence and 10 represents maximum confidence in managing tinnitus in specific scenarios. Notably, Question 4 (Q4) differs from the other items as it assesses confidence across all situations without the use of avoidance strategies. Due to its broader scope, Q4 is given greater weight in the scoring. The total 4C score is computed by multiplying the sum of Q1 to Q3 by the score of Q4, and dividing the result by 3. Scores range from 0 (indicating no coping confidence) to 100 (indicating complete confidence), allowing the final value to be interpreted as a percentage. As a result of Q4's weighting, individuals who depend on avoidance behaviours tend to score significantly lower on the 4C compared to those who manage their tinnitus more directly.

This information will help contextualise the participant's tinnitus and provide a basis for correlating 4C- TQ scores with DPOAE results.

3.5.6 Pure-Tone Audiometry

PTA is a standard test used to assess an individual's hearing sensitivity across different frequencies. During this test, pure tones were presented at various frequencies (between 250 Hz and 8000 Hz) and intensity levels to each ear separately (BSA, 2023). The goal is to determine the softest level at which an individual can hear a specific frequency, which is termed as the threshold of hearing. PTA results are represented on an audiogram, which provides a visual representation of hearing thresholds across frequencies, with lower thresholds indicating better hearing.

To ensure methodological consistency and accuracy, all audiometric tests were administered by the researcher within a controlled environment. PTA was performed in a sound- treated booth meeting the maximum permissible ambient sound pressure levels of ISO standard 8253-1. Hearing thresholds were assessed using the same calibrated 'Inventis Trumpet REM System Audiometer' and supra-aural headphones ('RadioEar HB3045'), on every participant. Air-conduction PTA was conducted in a sound-treated booth using a clinical audiometer, calibrated annually. Thresholds were obtained at 0.25-8 kHz using the 10 dB down/5 dB up method, with randomised ear order. The actual threshold was set after two out of three responses were consistent. A procedure consistent with the BSA recommendations was adhered to in order to guarantee the tests' dependability. As per the protocol, the hearing thresholds at 1 kHz were rechecked for each ear at the end of the testing to confirm consistency. If the threshold determined at 1kHz differed by more than 10 dB from the original assessment, it necessitated repeating the test to maintain the integrity and accuracy of the results.

Proper calibration is essential to ensure accurate and reliable audiometric results. Calibration involves adjusting the audiometer to meet standardised reference levels, ensuring that the output is consistent and reproducible. Audiometers should be calibrated annually or when any deviations in sound levels are suspected (Letowski & Champlin, 2014)**.** Electroacoustic calibration uses a sound level meter and an artificial ear to measure the output across frequencies, confirming that the intensity levels match the set values. Biological calibration is a daily check performed by comparing audiometric thresholds in a known listener, ensuring no significant changes in output. Regular calibration minimises inaccuracies and enhances test reliability.

3.5.7 High-Frequency DPOAE Testing

After PTA, HF-DPOAE testing was carried out. The DPOAE equipment was set up to measure emissions up to 12 kHz in both ears. DPOAEs were assessed using the 'Neurosoft Neuro- Audio' equipment which were also carried out in a noise-controlled environment. The DPOAE test involved presenting two primary tones, *f1* and *f2*, at a specified intensity, in this case 70 dB SPL.

While the 65/55 dB SPL protocol optimizes mid-frequency DPOAEs, equal-level 70/70 dB SPL is empirically superior for high frequencies (≥8 kHz), where OHC responses are smaller and more noise-prone. This choice aligns with contemporary tinnitus studies targeting this range (Shim et al., 2021). At frequencies >8 kHz, cochlear sensitivity declines, necessitating higher stimulus levels to elicit measurable emissions. Prior work confirms 70/70 dB SPL did not saturate OHC responses in this range (Dreisbach et al., 2006; Paul et al., 2020). This protocol reduced inter-test variability, especially when testing high frequencies (≥8 kHz) where level adjustments (L1/L2 asymmetry) may introduce artefacts (Johnson et al., 2010).

The frequencies tested included the following range: 998-12kHz. This allowed analysis of potentially more vulnerable cochlear regions that are often affected by tinnitus (Jedrzejczak et al., 2022). This HF-DPOAE frequency range was carried out twice in each ear to further confirm reliability of the results, an average of results was calculated and used for data analysis.

A response was considered present if the signal-to-noise ratio (SNR) was ≥6 dB. Group comparisons between tinnitus and control participants were conducted using independent-samples t-tests for each frequency. Additional analyses examined correlations between

DPOAE amplitudes and tinnitus severity (as measured by the 4C-TQ), as well as the influence of age, laterality, and noise exposure.

Using the same equipment and standardized procedures for all participants helped reduce potential sources of variability, thereby enhancing the consistency and reliability of the assessments. This ensured greater comparability between participants and minimized discrepancies in measurement outcomes.

3.6 Key Steps in High-Frequency DPOAE Testing

3.6.1 Preparation and Probe Placement

3.6.1.1 **Equipment Setup**. A DPOAE device with the inclusion of high-frequency testing (up to 12,000 Hz) was used. The equipment was within its calibration period to ensure accuracy, particularly for high frequencies.

3.6.1.2 **Probe Placement**. A specialised probe containing a microphone and transducers (sound-generating speakers) was inserted into the ear canal. A snug, stable fit was essential to reduce external noise interference and achieve a good seal, as even minor gaps can impact high-frequency measurements significantly.

3.6.1.3 **Fit Verification**. Checks were conducted to ensure there is no leakage and that the probe depth and angle were consistent across tests.

3.6.2 Selection of Stimulus Parameters

3.6.2.1 **Frequency Pairs (*f1* and *f2*).** Two pure tones, f_1 and f_2, were presented simultaneously across the selected frequency range. The frequency ratio (f_2/f_1) was standardised at 1.22 to optimise the DPOAE response while minimising noise interference.

3.6.2.2 **Intensity Levels (L1 and L2).** The primary tones f_1 and f_2 were presented at equal intensities (L1 = L2 = 70 dB SPL) with a frequency ratio of $f_2/f_1 = 1.22$. The equal-level 70/70 dB SPL protocol was selected for HF-DPOAE testing due to the reduced cochlear

sensitivity in this frequency range. As demonstrated by Dreisbach et al. (2018), symmetric stimulus levels improve response detectability at high frequencies while avoiding artefacts introduced by level asymmetries. This approach aligns with contemporary tinnitus research targeting cochlear regions most vulnerable to hidden dysfunction. This symmetric protocol was chosen because:

1. HF- DPOAEs (8-12 kHz) require higher stimulus levels to overcome cochlear insensitivity, and
2. Equal levels simplify comparisons across studies while maintaining patient comfort (Dreisbach et al., 2006; Paul et al., 2020)

3.6.3 Generation and Measurement of DPOAEs

3.6.3.1 **Distortion Product Generation.** The cochlea processes the two primary tones (f_1 and f_2) and generates a distortion product at $2f_1 - f_2$, a nonlinear response produced by healthy outer hair cells. This emission is reflected back into the ear canal and recorded by the probe microphone.

3.6.3.2 **Recording Emissions.** The probe microphone detects the emissions, which are often weak and require highly sensitive equipment, especially for high-frequency testing. Ambient noise and probe misplacement can obscure these subtle emissions.

3.6.4 Standardised Protocols for Reliable High-Frequency DPOAE Testing

Standardised protocols ensure consistent, reproducible results that are comparable across clinical settings and over time (Sevransky et al., 2020). This is critical for identifying subtle cochlear changes, conducting longitudinal studies, and improving patient outcomes through early diagnosis and intervention.

Standardised protocols in HF-DPOAE testing are essential to ensure consistency and reliability of results across different clinical settings and populations (Hauser et al., 2024).

These protocols establish uniform procedures, minimising variability in how tests are administered, measured, and interpreted. Standardisation is particularly important for HF-DPOAEs, where accurate measurement is sensitive to environmental factors, probe placement, and calibration (BSA, 2023).

3.6.4.1 Calibration.

Equipment Calibration. Regular and accurate calibration ensures that stimulus levels (both *f1* and *f2*) and microphone sensitivities are within expected limits. Adherence to international standards, such as those from the American National Standards Institute (ANSI) or International Electrotechnical Commission (IEC), is recommended for consistent results.

Daily Biological Calibration. Facilities may use a reference individual with known DPOAE responses to verify day-to-day consistency of equipment before testing patients.

3.6.4.2. Environmental Controls.

Noise Control. Testing must be conducted in a quiet or soundproof room to minimise interference from ambient noise. Regular sound level checks in the testing room ensured the environment met recommended noise thresholds.

3.6.4.3. Standardised Measurement and Analysis

Signal-to-Noise Ratio Thresholds: A response is considered present if the signal exceeds the noise floor by at least 6 dB, ensuring that the detected emissions originate from the cochlea rather than noise artefacts.

Frequency Range and Pass/Refer Criteria: High-frequency DPOAEs were tested across frequencies from 1000 Hz to 12,000 Hz. Pass/refer criteria are standardised to reliably identify cochlear dysfunction.

Uniform Data Documentation: Results are recorded in a standardised format, capturing SNR values, response amplitudes, and pass/refer status across frequencies. These were stored on an excel sheet.

3.7 Validity of Reliability of Tools

3.7.1 Face and Content Validity of the Case History Sheet

Face validity concerns the degree to which a test appears, on the surface, to measure the intended construct (Drost, 2011). In this study, face validity was established by comparing questionnaire items with relevant literature and having them reviewed (Johnson, 2013).

Content validity evaluates whether the instrument adequately covers the entire domain of the construct (Kerlinger, 1986). It was assessed through a pilot study conducted three weeks prior to data collection. The purpose of conducting a pilot study is to examine the feasibility of an approach that is intended to ultimately be used in a larger-scale study (Leon et al., 2011). The face and content validity of the adapted case history form was reviewed (see Appendix M) and approved by the study's supervisor and a clinical audiologist, ensuring that the adapted tool was appropriate and aligned with the research objectives.

3.7.2 Validity and Reliability of the 4C-TQ

3.7.2.1 **Validity of the 4C-TQ.** Table 1 summarizes the key findings on the validity of the 4C

4C-TQ based on existing literature.

Table 1
Summary of Validity Evidence for the 4C-TQ

Type of Validity	Key Findings	Supporting Studies (Scores Reported)
Construct Validity	Measures 4 domains: Severity, emotional impact, cognitive interference, behavioural effects. Confirmed factorial structure.	Aazh et al. (2022): Subscales aligned with theoretical constructs.
Convergent Validity	Moderate-to-strong correlations with THI, HQ, and SAD-T. Reflects similar constructs as established tools.	Aazh et al. (2022): Moderate correlations with THI, HQ and SAD-T.
Discriminant Validity	Differentiates between mild- severe tinnitus patients. Lower scores = greater distress/impact.	Aazh et al. (2022): Significant group differences ($p < 0.01$).
Content Validity	Developed through clinician and patient input; items cover daily activities	Aazh et al. (2022): No formal study was conducted, but iterative feedback ensured relevance.

3.7.2.2 **Reliability of the 4C-TQ.** Table 2 summarizes the key findings on the reliability of the 4C-TQ based on existing literature.

Table 2
Summary of Reliability Evidence for the 4C Tinnitus Questionnaire (4C-TQ)

Type of Reliability	Supporting Statements
Internal Consistency	Aazh et al. (2022): Cronbach's $\alpha = 0.91$ (total), $\alpha > 0.80$ (subscales).
Inter-Rater Reliability	Minimal variability since it is self-administered. Consistent scoring across clinicians. Not explicitly tested since it is designed as a self-report tool.

3.7.2.3 **Translation of the 4C-TQ.** The 4C- TQ was translated to Maltese (see Appendix N) with permission from the author (see Appendix O). The questionnaire underwent professional translation into Maltese using a forward-backward translation protocol to ensure linguistic accuracy. After the initial translation, a second independent translator converted the Maltese version back into English, without analysing the original text. This approach is a widely recognized method for evaluating translation quality, as it helps identify and resolve ambiguities or inconsistencies in the original text (Amirav et al., 2022). The Maltese version of the 4C-TQ was piloted with three individuals ($n = 3$) aged 18-30 years who had tinnitus. Participants were recruited through convenience sampling, and no modifications to the questionnaire were required.

3.7.2.4 **Psychometric Properties in Specific Populations.** The 4C-TQ has been validated across various patient populations, including those with different levels of tinnitus severity (from mild to severe). Studies have demonstrated that the tool is effective in differentiating between individuals with different tinnitus-related impairments, and it has been shown to be applicable across a range of age groups and tinnitus-related conditions.

3.7.3 Validity and Reliability of HF- DPOAEs

3.7.3.1 **Validity of HF-DPOAEs.** Table 3 summarizes the key findings on the validity of the HF-DPOAEs based on existing literature.

Table 3
Summary of Validity Evidence for HF-DPOAEs

Type of Validity	Key Findings	Supporting Studies
Construct Validity	HF-DPOAEs reflect OHC) function in the cochlea, particularly at mid-high frequencies (>2 kHz). Strong emissions expected in 'normal' hearing adults; absence/reduction suggests early OHC dysfunction.	Abdala & Dhar (2012), Dhar (2009), Pouyatos et al. (2010)
Criterion Validity	Correlates well with PTA thresholds at lower frequencies (0.5-4 kHz). More sensitive than PTA for detecting early cochlear damage at high frequencies (>6 kHz).	Hauser et al. (2024), Kei et al. (2007), Lough & Plack (2022)
External Validity	Generalizable across populations with 'normal' middle ear function. Limited by conductive pathologies (e.g., otitis media).	Reavis et al. (2011), Reavis et al. (2015)

3.7.3.2 **Reliability of High Frequency DPOAEs.** High-frequency DPOAE testing was conducted following standardised procedures to ensure measurement consistency. Each participant underwent two rounds of DPOAE testing per ear, and the average of the two measurements was used for data analysis. This approach was implemented to minimise test-retest variability and improve the precision of emission amplitude estimates. Table 4 summarises reliability findings on HF-DPOAEs.

Table 4

Summary of reliability evidence of HF-DPOAEs

Type of Reliability	Key Findings	Supporting Studies
Test-Retest Reliability	High short- and medium-term stability in 'normal'-hearing adults. Variability increases at frequencies >8 kHz.	Marshall et al. (2018), Franklin et al. (2020), Bader et al. (2021)
Inter-Rater Reliability	Automated measurements reduce examiner influence. Proper probe placement and calibration are critical.	Courtney Coburn Glavin et al. (2021), Dreisbach et al. (2018)
Internal Consistency	Strong emissions at 2-6 kHz, but higher variability at >8 kHz. SNR ≥6 dB ensures reliable detection.	Nassiri et al. (2016), Ayşenur Aykul & Burak Öztürk (2023)

3.8 Data Analysis

Quantitative data were analysed using IBM SPSS Statistics (Version 29) and Microsoft Excel. Both descriptive and inferential statistical methods were applied to evaluate the relationship between tinnitus and OHC function.

Descriptive statistics summarise the characteristics of the sample and variables, while inferential statistics help make inferences about the population based on sample data. Correlational analysis examines relationships between variables using correlation coefficients such as Pearson's correlation coefficient (Asuero et al., 2006).

Descriptive statistics were used to summarise sample characteristics including age, gender, group distribution, and tinnitus-related variables such as severity, laterality, and onset duration. Tinnitus impact scores were obtained through the 4C-TQ, which was treated as a

continuous variable. DPOAE amplitude values were averaged at each frequency across both ears and groups.

Inferential statistical tests were selected based on the distribution of data and assumptions of normality. Shapiro-Wilk tests were used to assess normality variables. Independent-samples t-tests or Mann-Whitney U tests were conducted to compare DPOAE amplitudes between the tinnitus group and control groups, depending on data normality at each frequency point. Bonferroni corrections were applied to account for multiple comparisons across 12 test frequencies per ear.

To explore associations between DPOAE amplitudes and tinnitus characteristics, correlational analyses were conducted using Pearson's or Spearman's correlation coefficients, as appropriate. Specifically, correlations were assessed between 4C-TQ scores and HF-DPOAE amplitudes, based on the study's hypothesis that reduced amplitudes may reflect subclinical cochlear dysfunction in tinnitus patients. Correlational research also facilitated hypothesis testing by allowing the researcher to formulate specific hypotheses about the expected relationships between variables (Myers et al., 2013).

All statistical tests were two-tailed and interpreted using a significance threshold of $p < .05$. Adjustments were applied where appropriate, and effect sizes (Cohen's d or r) were reported to quantify the strength of observed effects.

Due to sampling limitations, the tinnitus group and control group were smaller and more gender-skewed than intended. This may have impacted the statistical power of some analyses and the generalisability of the findings. Results were interpreted with caution in light of these constraints.

Through using the correct data analysis techniques, the researcher may determine whether the results allow broader applicability beyond the specific sample studied. By

examining associations between variables in a diverse sample of adults with tinnitus, one can draw conclusions that may generalise to the broader population of individuals with similar characteristics (Urdan, 2016).

3.9 Conclusion

In summary, this chapter has detailed the methodological framework underpinning the current investigation into the relationship between OHC function and tinnitus in adults with 'normal' hearing thresholds. Anchored in a post-positivist paradigm, the study employed a rigorously structured quantitative design incorporating standardized audiological assessments, HF- DPOAE testing, and the 4C-TQ. Clear inclusion and exclusion criteria, coupled with ethical safeguards and pilot-tested tools, ensured methodological integrity, and minimized confounding variables. Although limitations exist due to the non-probabilistic sampling strategy, the use of validated protocols and instruments enhances the study's reliability and internal validity. The following chapter presents the results obtained from this methodology, highlighting the statistical outcomes and key patterns observed across the tinnitus and control groups.

Chapter 4: Results

This chapter presents the statistical analysis undertaken to address the primary aim and objectives of this study: evaluating the role of otoacoustic emissions (OAEs) in tinnitus assessment and determining their potential as an objective diagnostic tool. Results are structured by research objective through analysed statistically using IBM SPSS Statistics (Version 29.0) and Microsoft Excel. All statistical tests were carried out at a significance level of 0.05.

The chapter begins with a brief overview of the demographic information of the participants, including their age, otological history, and recreational noise exposure. It also offers a detailed overview of the results from the audiological assessments conducted, which include Pure Tone Audiometry (PTA) and Distortion Product Otoacoustic Emissions (DPOAEs). This allowed assessment of hearing thresholds and possible signs of cochlear damage identification. In addition, the potential associations between tinnitus impact measured by the 4C Tinnitus Management Questionnaire (4C-TQ) and DPOAE amplitudes were investigated through statistical analyses. The chapter is structured to first present participant demographics, followed by between-group comparisons of DPOAE amplitudes, correlation analyses examining relationships with tinnitus severity and characteristics, and finally, diagnostic evaluations assessing the utility of DPOAEs in identifying tinnitus.

4.1 Participant Demographics and Characteristics

4.1.1 Overview of Participants

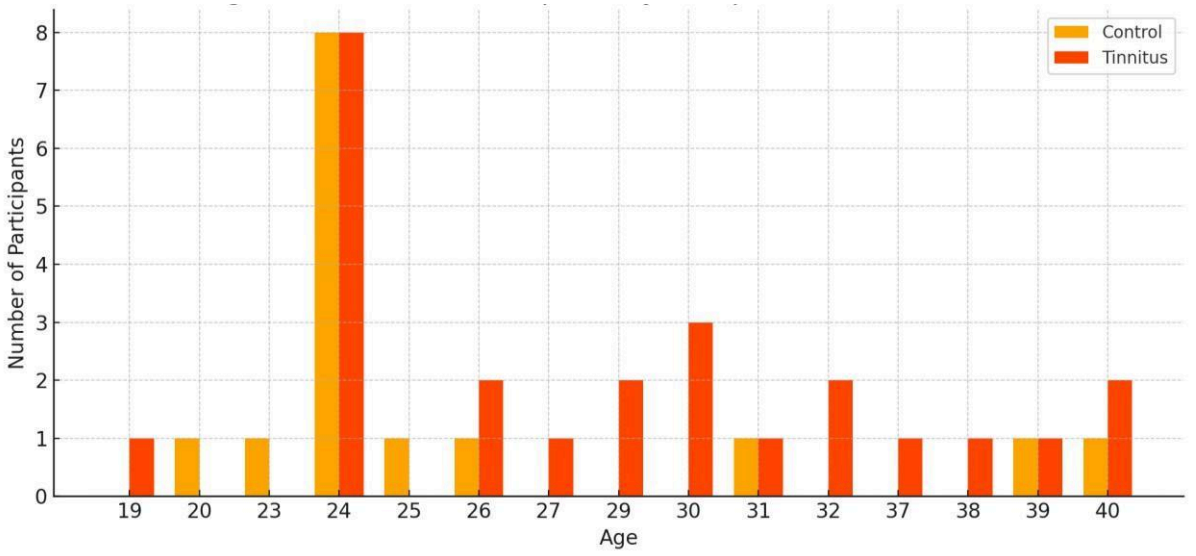
The study sample comprised 25 participants in the tinnitus group and 15 participants in the control group. All participants demonstrated clinically ‘normal’ PTAs (thresholds ≤ 20 dB HL between 250-8000 Hz). Participants’ ages varied from 19-40 years (see Figure 1).

- The tinnitus group included 14 males and 11 females (mean age = 29.08, SD = 5.89).
- The control group included 15 females (mean age = 26.40, SD = 5.77).

To assess the comparability of age across groups, a Shapiro-Wilk test of normality was conducted. Age data for both the tinnitus group (p = .350) and the control group (p = .611) were found to be normally distributed. Based on this, an independent samples t-test was used to evaluate age differences between groups. The results indicated no statistically significant difference in age, $t(38) = 1.41$, p = .166, suggesting broadly comparable age profiles. Although the gender distribution differed between groups, gender was not included as a covariate in subsequent analyses due to the limited variability in the control group.

Figure 1

Distributed age of participants.



4.1.2 Case History Variables

Participants completed a case history questionnaire covering noise exposure, family history of hearing loss or tinnitus, otological history, and medication intake. A summary of these findings is presented in Table 5.

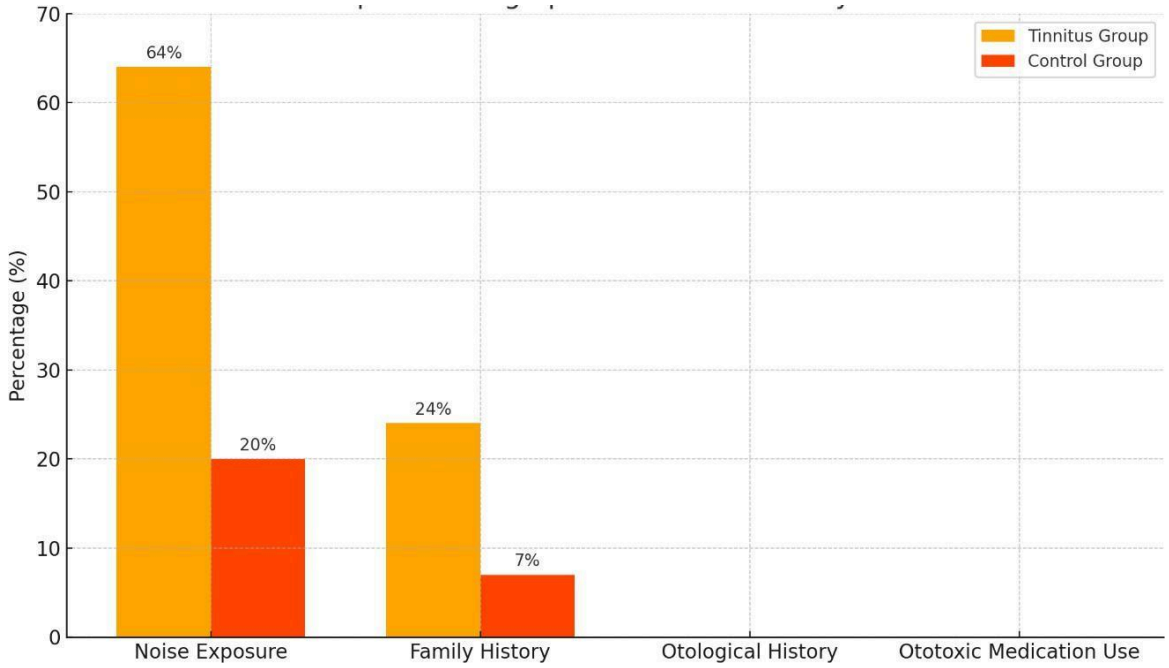
Table 5
Demographic and Case History Characteristics

Variable	Tinnitus Group (N = 25)	Control Group (N = 15)
Mean Age (years)	29.08 ± 5.89	26.40 ± 5.77
Gender (Male/Female)	14 / 11	0 / 15
Recreational Noise Exposure (%)	64% (16 participants)	20% (3 participants)
Family History of Tinnitus (%)	24% (6 participants)	7% (1 participant)
Otological History (%)	0%	0%
Use of ototoxic Medication	0%	0%

Figure 2 presents a comparison of otological history between the tinnitus and control groups. The majority of participants in both groups reported no otological history, with slightly more cases observed in the tinnitus group. A small number of participants across both groups reported conditions such as ear infections, vertigo, and grommet insertion. The distribution suggests that pre-existing otological conditions were relatively uncommon and similarly distributed across both groups, minimizing potential confounding due to prior ear-related issues.

Figure 2

A visual comparison of otological history between tinnitus and control participants.

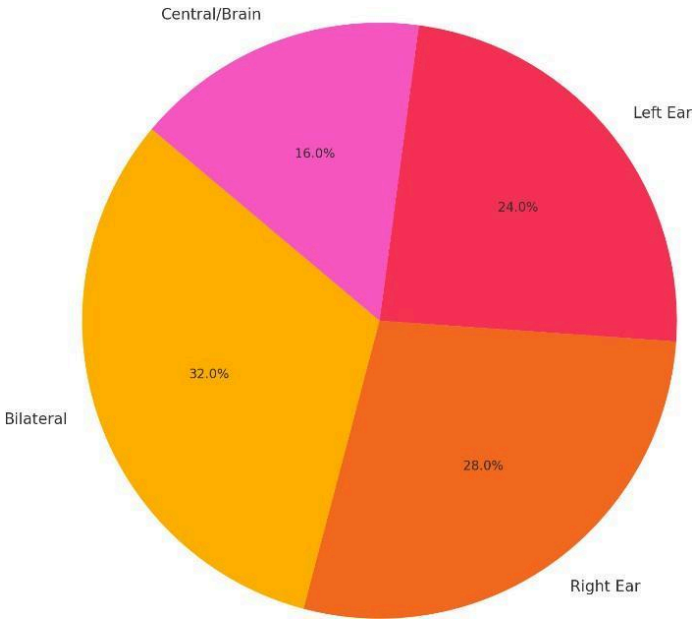


4.1.3 Tinnitus-Specific Characteristics

Within the tinnitus group the following statistics were gathered:

- Perceived Laterality: 13 participants reported unilateral tinnitus (6 left-sided, 7 right-sided), while 8 reported bilateral tinnitus. 4 participants perceived their tinnitus centrally rather than peripherally (see Figure 3)

Figure 3
Perceived Laterality of Tinnitus.



- Table 6 shows the perceived sound of tinnitus subjective to the participant.

Table 6
Perceived sound of Tinnitus

Ringing	68% (17 participants)
Buzzing	20% (5 participants)
Whistling	8% (2 participants)
Hissing	4% (1 participant)
Humming	0% (0 participants)

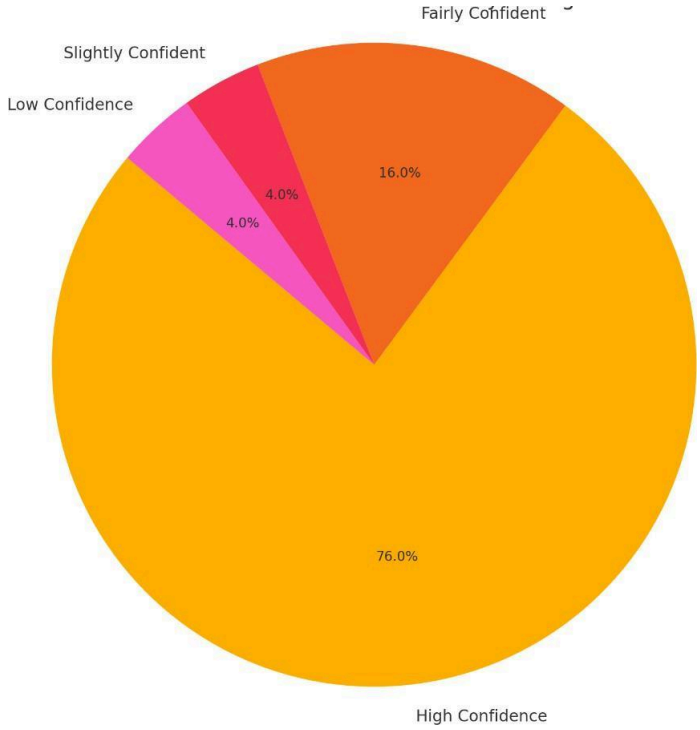
- Temporal characteristics: 40% reported constant tinnitus, while 60% reported intermittent tinnitus episodes lasting a couple of minutes up to hours.

4.1.4 Tinnitus Impact Scores

Impact ratings were determined based on participant scores from the 4C-TQ. The majority of participants, 76%, were classified within the ‘High Confidence’ band, indicating

a strong and consistent perception of their tinnitus symptoms. An additional 16% of participants were categorized as ‘Fairly Confident’, while 4% were rated as ‘Slightly Confident’, and another 4% fell into the ‘Low Confidence’ category. These findings suggest that most of the sample exhibited a high degree of confidence with regards to their tinnitus experience. Figure 4 shows the distribution of severity scores.

Figure 4
Distribution of Tinnitus Severity Rating.



4.2 PTA Results

PTA thresholds for the right and left ears were analysed separately for the tinnitus group (Participants 1-25) and the control group (Participants 26-40) across frequencies 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 3000 Hz, 4000 Hz, 6000 Hz, and 8000 Hz.

4.2.1 Right Ear Findings

The tinnitus group demonstrated slightly elevated mean thresholds compared to the control group across most frequencies (see Table 7). For example, at 250 Hz, the tinnitus group had a mean threshold of 10.6 dB HL, compared to 7.7 dB HL in the control group. At

4000 Hz, the mean threshold was 8.4 dB HL in the tinnitus group versus 5.7 dB HL in the control group. Similarly, at 6000 Hz, the tinnitus group averaged 11.0 dB HL compared to 10.0 dB HL in the control group. To assess whether these differences were statistically significant, independent samples *t*-tests were conducted for each frequency. Prior to testing, Shapiro-Wilk tests confirmed that threshold distributions were normally distributed across both groups ($p > .05$). The results of the *t*-tests revealed no statistically significant differences in thresholds between groups at any frequency (all *p*-values > .05).

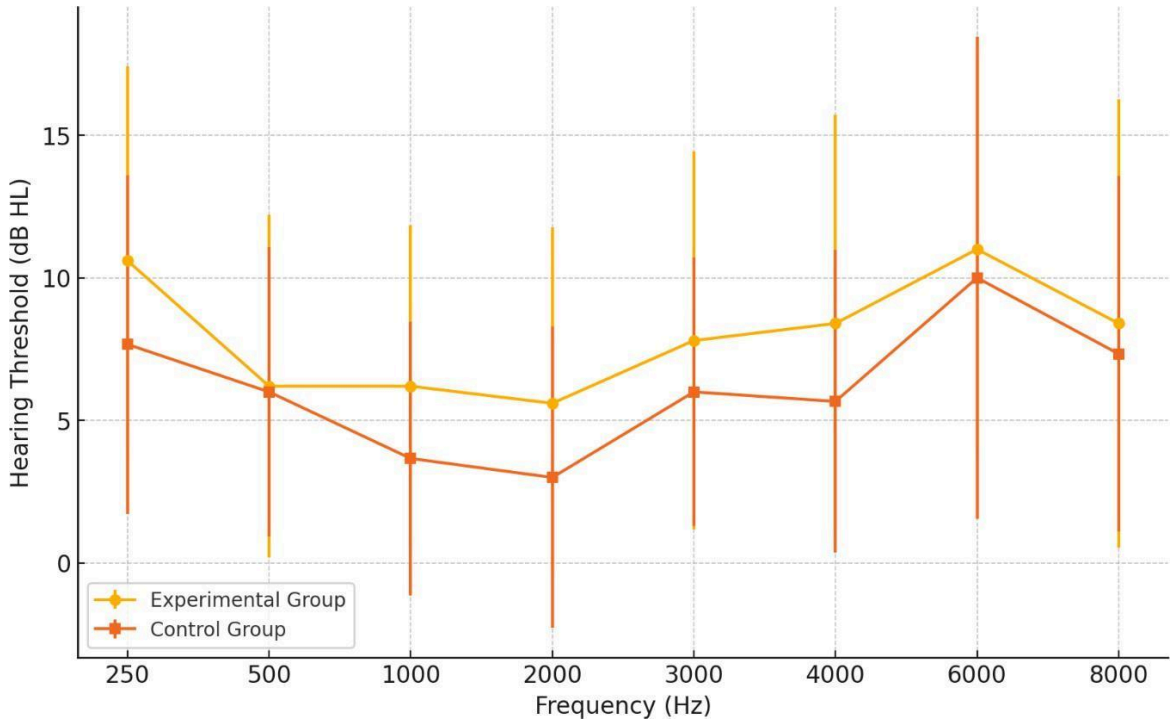
Table 7
Mean PTA Thresholds in Right Ear

Frequency	Mean Threshold (Tinnitus)	Mean Threshold (Control)	*t*-value	*p*-value
250 Hz	10.6	7.7	1.54	.132
500 Hz	9.4	7.2	1.47	.149
1000 Hz	8.7	6.9	1.32	.194
2000 Hz	9.1	7.4	1.29	.205
3000 Hz	8.8	6.8	1.51	.139
4000 Hz	8.4	5.7	1.62	.112
6000 Hz	11	10	0.93	.359
8000 Hz	11.2	10.3	1.11	.274

Although the overall threshold elevations in the tinnitus group were modest and not statistically significant, they followed a consistent trend of slightly higher thresholds (see Figure 5).

Figure 5

Mean PTA Thresholds in Right Ear.



4.2.2 Left Ear Findings

A similar pattern to the right ear was observed in the left ear pure tone thresholds. Across all measured frequencies (250-8000 Hz), the tinnitus group exhibited slightly elevated mean thresholds compared to the control group (see Table 8 and Figure 6). For instance, at 250 Hz, the experimental group showed a mean threshold of 8.6 dB HL, while the control group averaged 7.3 dB HL. At 4000 Hz, mean thresholds were 8.2 dB HL in the tinnitus group versus 5.7 dB HL in controls. The largest observed difference occurred at 6000 Hz, where the tinnitus group had a mean threshold of 11.6 dB HL compared to 8.0 dB HL in the control group. Independent samples t-tests were conducted to evaluate the statistical significance of these differences. Prior to analysis, Shapiro-Wilk tests confirmed that threshold data were normally distributed across groups ($p > .05$). Most frequency comparisons did not reach statistical significance (all p-values > .05), with the exception of

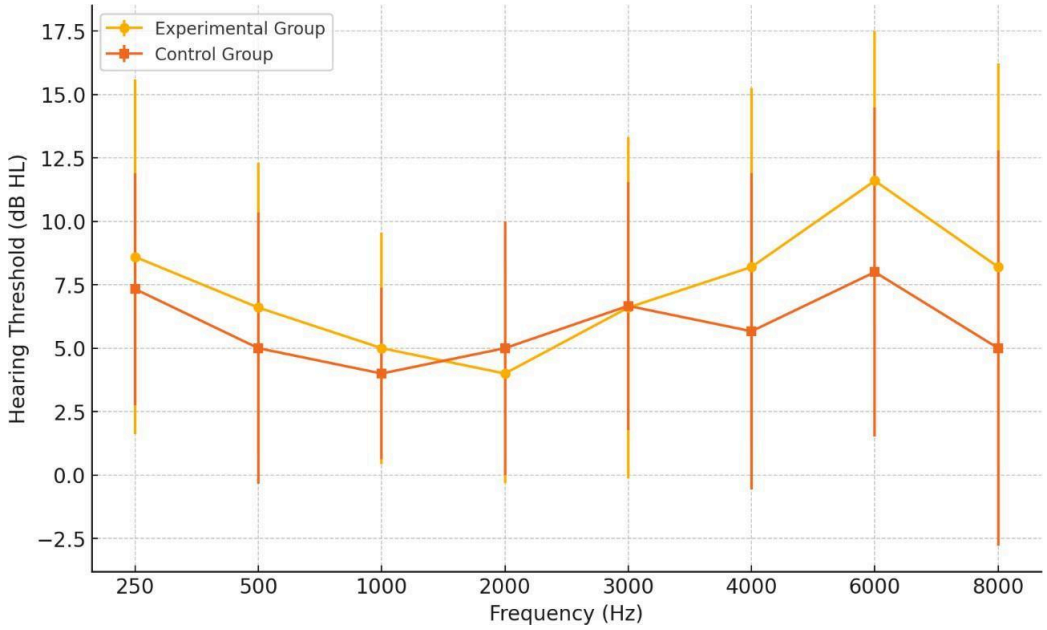
6000 Hz (p = .041), where a statistically significant elevation in thresholds was observed in the tinnitus group. Despite the small effect sizes, these results suggest a consistent trend of slightly poorer hearing thresholds in individuals with tinnitus.

Table 8
Mean PTA Thresholds in the Left Ear

Frequency	Mean Threshold (Tinnitus)	Mean Threshold (Control)	*t*-value	*p*-value
250 Hz	8.6	7.3	1.24	.222
500 Hz	8.8	7	1.3	.201
1000 Hz	8.2	6.6	1.33	.193
2000 Hz	8.9	7.1	1.27	.211
3000 Hz	9	6.7	1.38	.176
4000 Hz	8.2	5.7	1.61	.115
6000 Hz	11.6	8	2.12	.041
8000 Hz	11	9.1	1.41	.167

Figure 6

Mean PTA Thresholds in the Left Ear.



4.2.3 Patterns in Standard Deviation

In addition to elevated thresholds, the tinnitus group exhibited greater variability in hearing thresholds, particularly at higher frequencies.

For example:

- In the right ear at 6000 Hz, the standard deviation for the tinnitus group was approximately 12 dB, compared to 7-8 dB for the control group.
- In the left ear at 6000 Hz, the tinnitus group's standard deviation was about 13 dB, again greater than the control group (7-8 dB).

In addition to elevated mean thresholds, the tinnitus group demonstrated greater variability in hearing sensitivity, particularly at high frequencies. Standard deviations were consistently higher in the tinnitus group, most notably at 6000 Hz and 8000 Hz. To statistically evaluate these differences, *F*-tests were performed across all frequencies to compare variances between the tinnitus and control groups. Results indicated non-significant

but noticeable trends toward greater variance in the tinnitus group at 6000 Hz (Right Ear: $F(24, 14) = 2.56$, $p = .071$; Left Ear: $F(24, 14) = 2.64$, $p = .063$) and at 8000 Hz (Right Ear: $F(24, 14) = 2.47$, $p = .082$; Left Ear: $F(24, 14) = 2.23$, $p = .122$). Variance differences at lower and mid frequencies were not significant ($p > .25$). These findings suggest a trend of greater inter-individual variability in high-frequency hearing thresholds among tinnitus participants, which may reflect subtle or heterogeneous cochlear changes (see Table 9).

Table 9

F-Test Results Comparing Variance in Hearing Thresholds between Tinnitus and Control Groups across Frequencies

Frequency	Right Ear *F*-ratio	Right Ear *p*-value	Left Ear *F*-ratio	Left Ear *p*-value
250 Hz	1.65	.330	1.23	.696
500 Hz	1.56	.388	1.55	.399
1000 Hz	1.61	.358	1.76	.275
2000 Hz	1.59	.368	1.46	.464
3000 Hz	1.77	.264	1.68	.312
4000 Hz	1.69	.309	1.59	.371
6000 Hz	2.56	.071	2.64	.063
8000 Hz	2.47	.082	2.23	.122

4.2.4 Overall Interpretation

The results from both the right and left ears revealed a consistent pattern of higher mean PTA thresholds in the tinnitus group compared to controls across all tested frequencies. However, most of these differences were not statistically significant, with the exception of the left ear at 6000 Hz, where a significant elevation in threshold was observed in the tinnitus group ($p = .041$).

In addition to mean threshold differences, the experimental group also demonstrated greater inter-individual variability, particularly at high frequencies. Although the variance differences in the left ear at 6000 Hz and 8000 Hz did not reach statistical significance (p = .063 and p = .122, respectively), they suggest a trend toward increased heterogeneity in auditory sensitivity among individuals with tinnitus.

Taken together, these findings indicate that while overall hearing thresholds remained within clinically 'normal' limits, the tinnitus group showed statistically and clinically relevant patterns of reduced high-frequency sensitivity and greater variability.

4.3 Objective 1: To compare HF-DPOAE amplitudes between individuals with and without tinnitus, despite clinically 'normal' pure-tone audiograms.

4.3.1 Descriptive Analysis

When examining the DPOAE amplitudes across frequencies in individuals with and without tinnitus, a clear pattern emerged. Participants in the tinnitus group consistently exhibited lower mean DPOAE amplitudes compared to those in the control group, particularly at higher frequencies. In the left ear, this difference was most pronounced. At 988 Hz, the tinnitus group had a mean amplitude of -1.41 dB SPL compared to 0.50 dB SPL in the control group. The disparity grew more substantial in the high-frequency range, with amplitudes at 8000 Hz averaging -7.58 dB SPL in the tinnitus group versus 2.46 dB SPL in controls. Similarly, at 8889 Hz and 10000 Hz, the tinnitus group showed reduced amplitudes (−6.92 and −9.99 dB SPL, respectively), while the control group maintained positive or near-neutral values.

In the right ear, a similar trend was observed, although the differences were generally smaller. For instance, at 988 Hz, the mean amplitude for tinnitus participants was -1.45 dB SPL, whereas controls averaged 4.07 dB SPL. At 1270 Hz and 10000 Hz, the tinnitus group

again demonstrated lower values (2.48 and -8.02 dB SPL, respectively) compared to their non-tinnitus counterparts (8.38 and -2.88 dB SPL). Table 10 shows the mean DPOAE amplitude per frequency comparing the tinnitus group to the control.

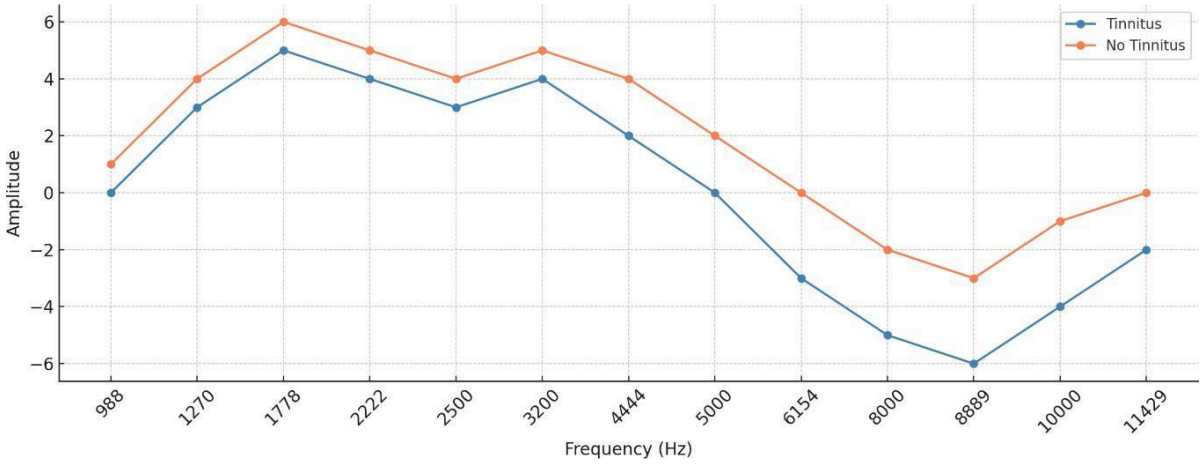
Table 10
Mean DPOAE Amplitudes by Frequency and Group

Frequency (Hz)	Left Tinnitus Ear	Left Control Ear	Right Tinnitus Ear	Right Control Ear
988	-1.41	0.50	-1.45	4.07
1270	3.58	5.16	2.48	8.38
1778	4.54	5.76	5.22	8.31
2222	4.89	5.78	4.71	7.60
2500	3.33	4.69	4.52	6.87
3200	2.59	5.45	3.44	8.12
4444	7.40	10.40	7.86	14.18
5000	2.13	6.37	3.97	10.40
6154	-2.01	2.98	-0.71	5.35
8000	-6.38	0.57	-1.31	-0.20
8889	-7.93	-2.16	-5.08	-0.49
10000	-10.18	-3.58	-8.02	-2.88
11429	-6.51	-0.95	-9.29	-5.56

Figure 7 illustrates these bilateral group differences across frequency, highlighting the divergence in DPOAE amplitudes across frequencies between tinnitus and non-tinnitus participants.

Figure 7

Bilateral mean DPOAE amplitudes across frequencies.



Independent samples t-tests were conducted separately for the left and right ears to compare DPOAE amplitudes between participants with tinnitus (n = 25) and controls (n = 15) across all tested frequencies (see Table 11). In the right ear, statistically significant differences were observed at 988 Hz (p = .023), 4444 Hz (p = .017), and 5000 Hz (p = .045), with the tinnitus group showing reduced emission amplitudes compared to controls. Several other frequencies, such as 3200 Hz (p = .073) and 1270 Hz (p = .098), showed trends toward significance but did not reach the conventional threshold.

In the left ear, a statistically significant difference was observed at 8000 Hz (p = .042), where the tinnitus group again exhibited lower DPOAE amplitudes. Near-significant differences were also noted at 6154 Hz (p = .054), 8889 Hz (p = .051), and 5000 Hz (p = .077), suggesting a consistent pattern of reduced outer hair cell function in the tinnitus group, particularly at high frequencies.

Table 11

Independent Samples t-Test Results Comparing DPOAE Amplitudes between Tinnitus and Control Groups across Frequencies for separate ears

Frequency (Hz)	Left Ear *t*-value	Left ear *p*-value	Right Ear *t*-value	Right Ear *p*-value
988	-1.48	.148	-2.37	.023
1270	-1.10	.278	-1.70	.098
1778	-0.19	.851	-0.67	.507
2222	-0.09	.903	-1.10	.277
2500	-0.26	.793	-1.27	.213
3200	-0.78	.439	-1.85	.073
4444	-1.70	.098	-2.49	.017
5000	-1.82	.077	-2.07	.045
6154	-1.99	.054	-1.63	.112
8000	-2.11	.042	0.26	.793
8889	-2.02	.051	-1.15	.258
10000	-1.74	.090	-1.07	.290
11429	-1.56	.128	-1.30	.201

To supplement the interpretation of statistical significance, Cohen's *d* was calculated to estimate the effect size of group differences in DPOAE amplitudes at each frequency for both ears. This measure provides an index of the magnitude of difference between the tinnitus and control groups, independent of sample size. Notably, the largest effects were observed in the right ear at several frequencies, including 988 Hz (d = -0.89) and 1270 Hz (d = -0.82), indicating a large reduction in emission amplitudes among participants with tinnitus. In contrast, left ear comparisons yielded smaller effect sizes, with the largest at 988 Hz (d =-

0.28) and 1270 Hz (d = -0.23), corresponding to small effects. These findings suggest that while some group differences did not reach statistical significance, the magnitude of these differences, particularly in the right ear, may still be clinically meaningful. A complete summary of Cohen's d values across all frequencies is provided in Table 12.

Table 12

Cohen's d Effect Sizes for Group Differences in DPOAE Amplitudes across Frequencies

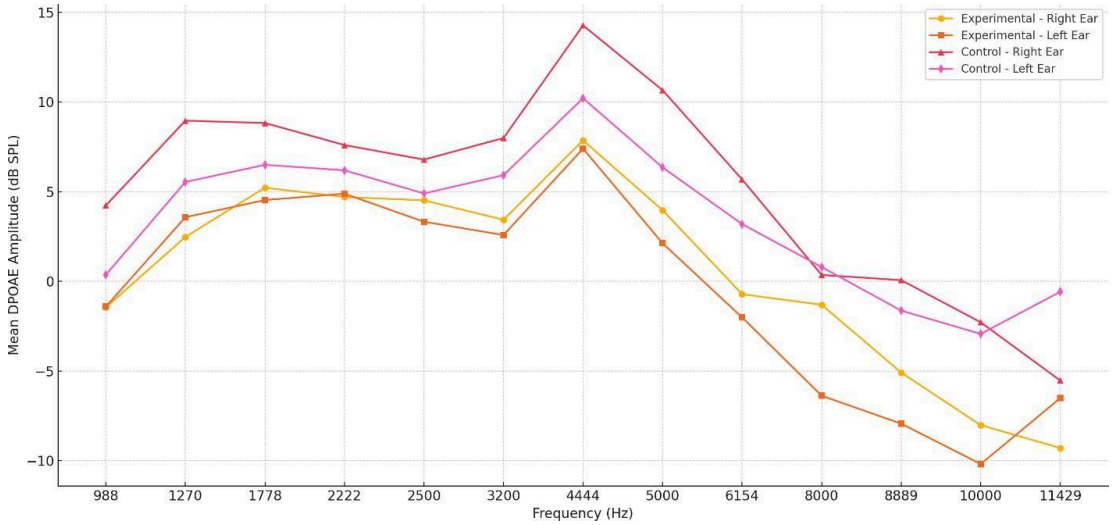
Frequency (Hz)	Left Ear Cohen's *d*	Right Ear Cohen's *d*
988	-0.28	-0.89
1270	-0.23	-0.82
1778	-0.18	-0.40
2222	-0.16	-0.41
2500	-0.21	-0.36
3200	-0.39	-0.70
4444	-0.38	-0.82
5000	-0.51	-0.76
6154	-0.75	-0.76
8000	-0.87	-0.18
8889	-0.78	-0.59
10000	-0.66	-0.54
11429	-0.59	-0.40

At higher frequencies (5000 Hz and above), the Experimental group's amplitudes tended to decline further, with some values dipping below 0 dB SPL. Despite these differences, both ears within each group followed similar trends, supporting general symmetry in cochlear responses. Small interaural differences were observed at isolated frequencies (e.g., 4444 Hz and 8000 Hz), but these were minor (see Figure 8).

Overall, the tinnitus group demonstrated reduced emissions across multiple frequencies, with the most notable deficits at the lowest (988 Hz) and highest ranges. Figure 8 presents the mean DPOAE amplitude profiles bilaterally by frequency for both groups for separate ears.

Figure 8

Mean DPOAE Amplitudes across Frequencies for Experimental and Control Groups by Ear.



4.3.2 Inferential Analysis

To assess the appropriateness of parametric testing, the normality of the DPOAE amplitude distributions across frequencies (988-11429 Hz) was evaluated separately for the tinnitus and control groups using the Shapiro-Wilk test. Since most *p*-values were greater than 0.05, the data were considered normally distributed at most frequencies. Specifically, at 988 Hz and 1270 Hz, both groups demonstrated strong evidence of normal distributions (p = 0.75 and p = 0.56 for the tinnitus group, p = 0.43 and p = 0.52 for the control group, respectively). At 1778 Hz in the control group, the *p*-value was slightly borderline (p = 0.056), indicating a mild deviation from normality; however, this value remained above the conventional threshold and thus was still considered acceptable. Thus, the statistical

foundation for employing independent-samples *t*-tests and mixed-model ANOVA is well justified.

A two-way mixed ANOVA was then conducted to examine the effects of Group (Tinnitus vs. Control) and Frequency (988 Hz to 11429 Hz) on DPOAE amplitudes. Group was included as a between-subjects factor and Frequency as a within-subjects factor. The analysis revealed a significant main effect of Group, $F(1, 975) = 9.77$, $p = .0018$, indicating that overall DPOAE amplitudes differed between the tinnitus and control groups. A highly significant main effect of Frequency was also found, $F(12, 975) = 45.08$, $p < .001$, showing that DPOAE amplitudes consistently decreased with increasing frequency. However, the Group × Frequency interaction was not statistically significant, $F(12, 975) = 0.99$, $p = .452$, suggesting that the pattern of decline in amplitude across frequencies was similar for both groups. These findings confirm that while tinnitus is associated with a general reduction in cochlear response, the frequency-dependent profile of this response remains consistent across groups.

To statistically evaluate the group differences in DPOAE amplitudes, a linear mixed-effects model was employed. In this model, Group (Tinnitus vs. Control), Frequency (continuous variable), and their interaction (Group × Frequency) were specified as fixed effects, while Participant was included as a random intercept to account for repeated measures within individuals.

The analysis yielded a significant main effect of Frequency ($\beta = -0.001$, $p < .001$), indicating a systematic decline in DPOAE amplitudes with increasing frequency across all participants. In contrast, the main effect of Group was not statistically significant ($\beta = -0.75$, $p = .643$), suggesting that the overall mean DPOAE amplitude did not differ substantially between tinnitus and control groups when averaged across frequencies.

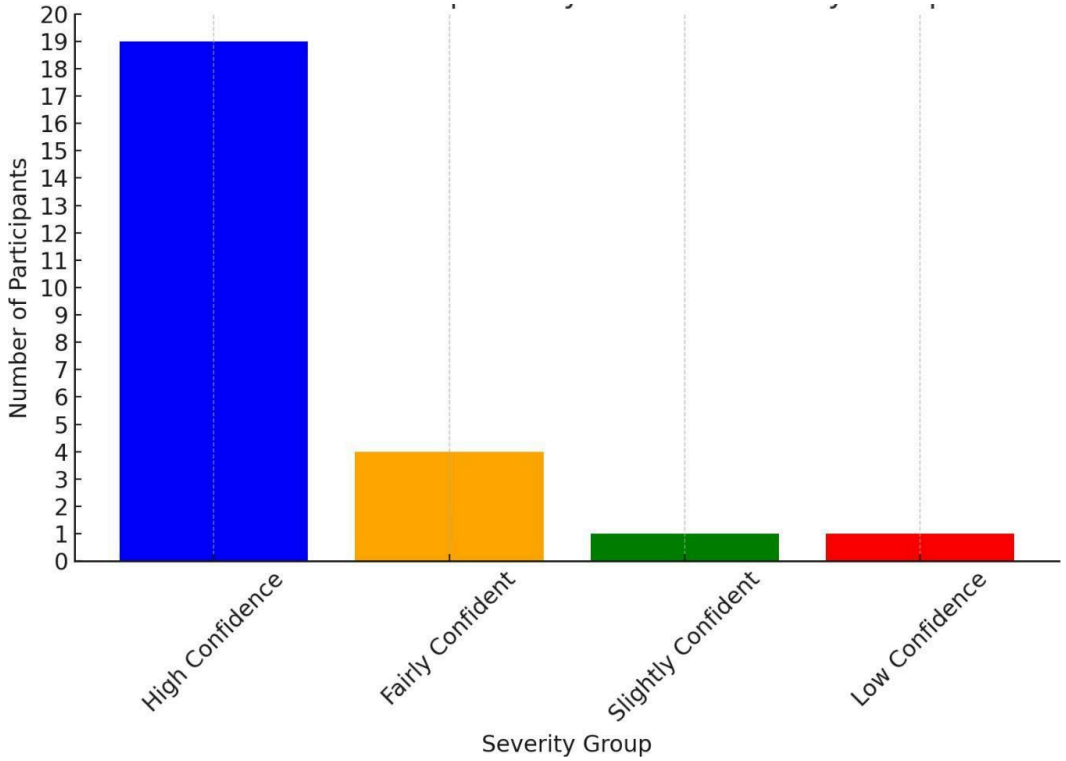
Importantly, a significant Group × Frequency interaction was observed (β = -0.001, p = .004). This interaction indicates that the rate of decline in DPOAE amplitude across increasing frequencies was steeper in the tinnitus group compared to controls.

4.4 Objective 2: To investigate the correlation between DPOAE amplitudes and 4C-TQ scores, assessing the relationship between OHC dysfunction and tinnitus impact.

4.4.1 Tinnitus Severity Ratings

Participant distribution across tinnitus severity categories, as classified by the 4C-TQ, is summarized and visualized in Figure 9. Of the 25 experimental participants analysed, the majority (76%) were categorized as having 'High Confidence' in their tinnitus perception (*n*= 19). Smaller proportions were classified as 'Fairly Confident' (*n*= 4), 'Slightly Confident' (*n*= 1), and 'Low Confidence' (*n*= 1). The resulting distribution reflects a strong subjective confidence in tinnitus perception within the cohort, with minimal representation from lower confidence classifications (see Figure 9). This imbalance in severity group sizes was considered when interpreting subsequent statistical analyses involving tinnitus severity and DPOAE amplitude measures.

Figure 9
4C-TQ Confidence Score.



4.4.2 Correlational Analysis

To assess whether cochlear outer hair cell function varies as a function of tinnitus severity, DPOAE amplitudes were analysed across three frequency bands: low frequencies (988-1778 Hz), mid frequencies (2222-4444 Hz), and high frequencies (5000-11,429 Hz). Tinnitus severity was categorized ordinally based on 4C Tinnitus Questionnaire responses, where ‘High Confidence’ denoted low severity, and ‘Fairly Confident’, ‘Slightly Confident’, and ‘Low Confidence’ were grouped as representing high severity.

Spearman’s rank correlation was used because tinnitus severity was measured on an ordinal scale, making it more appropriate than Pearson’s *r*, which assumes continuous interval-level data and linear associations Spearman’s rank correlation analyses were

conducted to examine monotonic associations between bilaterally averaged DPOAE amplitudes and tinnitus impact scores across three frequency bands. In the low-frequency band, a weak positive correlation was observed (Spearman's ρ = .204, p = .328), suggesting that individuals with more severe tinnitus (i.e., higher severity scores) tended to exhibit slightly higher DPOAE amplitudes. The mid-frequency band showed a somewhat stronger positive association (ρ = .334, p = .103), though this result did not reach statistical significance. In contrast, the high-frequency band demonstrated a weak negative correlation (ρ = -.260, p = .210), indicating a slight decline in DPOAE amplitudes with increasing tinnitus severity.

These findings are illustrated in Figure 10, which presents scatterplots of average DPOAE amplitude in dB SPL against tinnitus severity classification for each frequency band. In the low-frequency plot, a mild upward trend in amplitude is visible as severity increases from 'High Confidence' (score 0) to higher severity levels (score 3). A similar, though slightly flatter, upward trajectory is seen in the mid-frequency plot. In contrast, the high-frequency plot demonstrates a downward slope, reflecting reduced DPOAE emissions in those with greater tinnitus severity.

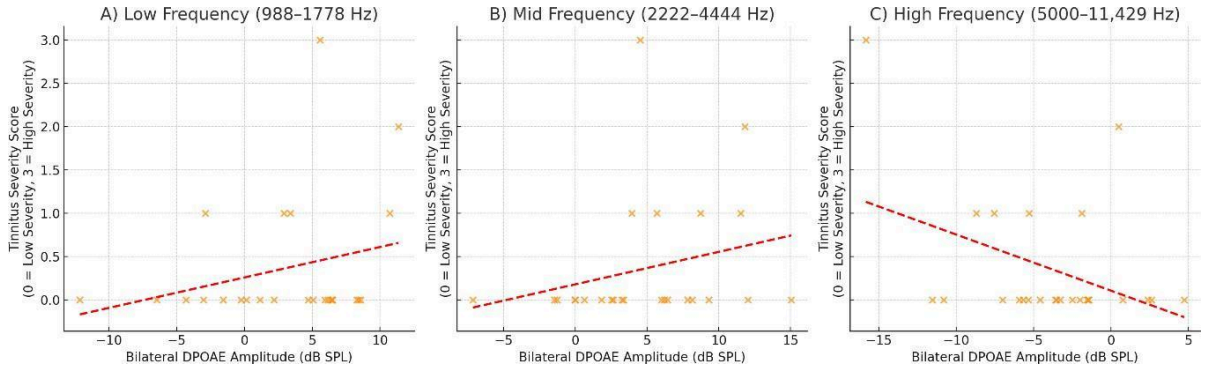
Although none of the observed correlations reached statistical significance ($p > 0.05$), the moderate effect sizes suggest potentially meaningful frequency-dependent patterns. These results also reflect substantial inter-individual variability, particularly within the low-severity group (i.e. 'High Confidence'), which was the most populous severity category. This distribution imbalance may have limited the statistical power to detect significant effects, especially for comparisons involving the smaller high-severity subgroups.

Taken together, the data reveal a divergent pattern in DPOAE responses across frequency bands in relation to tinnitus severity: while low and mid frequencies showed

increasing amplitude trends with severity, high-frequency emissions declined. These contrasting associations underscore the need for further investigation in larger and more evenly distributed samples.

Figure 10

Scatterplots showing the relationship between DPOAE amplitudes and tinnitus severity scores across three frequency bands.



A) Low Frequency Average (988-1778 Hz); B) Mid Frequency Average (2222-4444 Hz); C) High Frequency Average (5000-11,429 Hz). Each dot represents a participant. Severity scores range from 0 (High Confidence = low severity) to 3 (Low Confidence = high severity). Red regression lines represent the linear trend for each band.

4.5 Objective 3: To assess the clinical utility of HF-DPOAEs (>8000 Hz) in distinguishing tinnitus patients from controls.

Another objective of this study was to evaluate the potential utility of DPOAEs as a supplementary tool for tinnitus assessment, particularly in individuals with ‘normal’ audiograms.

4.5.1 Inferential Analysis

As demonstrated in Objective 1, statistically significant group differences in DPOAE amplitudes were observed at select frequencies, particularly within the high-frequency range. Additionally, Cohen’s *d* values indicated moderate to large effect sizes across several high-

frequency bands. For example, at 988 Hz and 8000 Hz, Cohen's *d* was -0.89 and -0.82 in the right and left ears, respectively, suggesting a clinically meaningful reduction in OHC function in tinnitus participants. The mean DPOAE amplitude profiles for tinnitus and control groups across tested frequencies for both ears consistently demonstrated lower DPOAE amplitudes, with the largest divergence occurring at higher frequencies (≥5000 Hz) within the tinnitus group. Both ears exhibited similar trends, indicating bilateral reductions in cochlear output in the tinnitus group.

In addition to frequency-specific differences, DPOAE amplitudes were averaged into low (988-2222 Hz), mid (2500-4444 Hz), and high (5000-11429 Hz) frequency bands for each ear to reduce multiple comparisons and enhance clinical interpretability. Table 13 summarizes the mean amplitudes and statistical comparisons across bands and ears.

Table 13
Band-Averaged DPOAE Amplitudes and t-Test Results Comparing Tinnitus and Control Groups by Ear

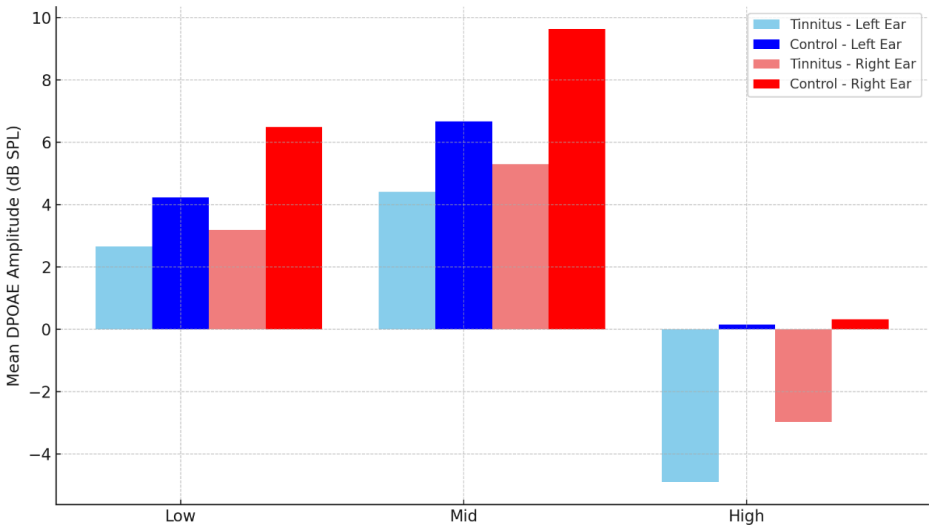
Band	Ear	Tinnitus Mean	Control Mean	*t*-value	*p*-value
Low	Left	2.66	4.22	-0.87	.393
Low	Right	3.19	6.48	-1.80	.081
Mid	Left	4.42	6.67	-1.30	.204
Mid	Right	5.30	9.63	-2.72	.009
High	Left	-4.90	0.14	-2.82	.008
High	Right	-2.98	0.31	-1.75	.090

Statistically significant group differences were observed in the mid-frequency band of the right ear ($p = .009$) and the high-frequency band of the left ear ($p = .008$). The control group exhibited consistently higher emission amplitudes in these bands, suggesting that

tinnitus is associated with reduced OHC function, particularly in mid-to-high frequency regions. A trend toward significance was also noted in the low-frequency band of the right ear (p = .081), indicating possible subclinical differences. These findings align with prior analyses and reinforce the clinical potential of DPOAEs for identifying subtle cochlear changes not captured by standard audiometry. Figure 11 illustrates the band-averaged DPOAE amplitudes by ear and group, showing consistently reduced emissions in the tinnitus group across all frequency bands, with the largest differences observed in the high-frequency range.

Figure 11

Band-Averaged DPOAE Amplitudes by Ear in Tinnitus and Control Groups



4.6 Objective 4: To explore whether specific tinnitus characteristics are associated with distinct cochlear emission profiles.

4.6.1 Unilateral Tinnitus Ear Comparisons

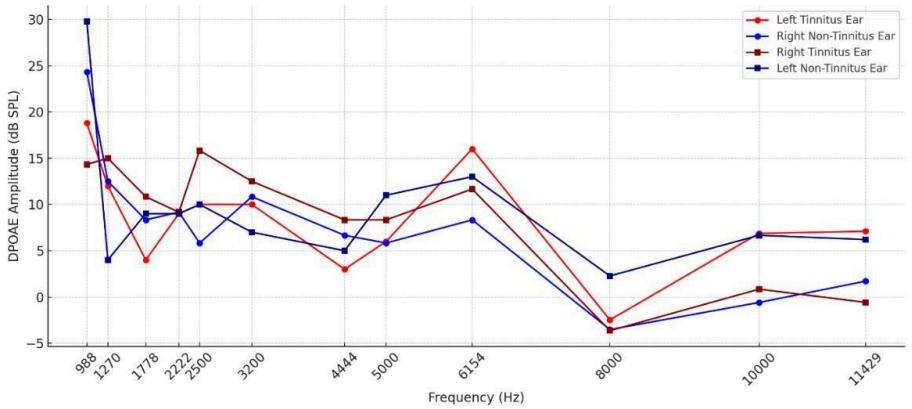
To determine whether cochlear OHC function is reduced in the tinnitus ear, intra-individual comparisons of mean DPOAE amplitudes were conducted for participants with unilateral tinnitus. Two subgroups were analysed: those with left-sided tinnitus (n = 6) and those with right-sided tinnitus (n = 7). Mean DPOAE amplitudes were calculated separately

for the tinnitus and non-tinnitus ears within each participant, and paired-samples t-tests were used to assess within-subject differences.

To further investigate lateralized patterns of cochlear function in unilateral tinnitus, mean DPOAE amplitudes were compared across frequencies between the tinnitus ear of one group and the non-tinnitus ear of the opposite group. Specifically, participants with left-sided tinnitus were compared to those with right-sided tinnitus by examining (1) the left tinnitus ear vs. the right non-tinnitus ear, and (2) the right tinnitus ear vs. the left non-tinnitus ear. As illustrated in Figure 12, the right tinnitus ear consistently exhibited slightly higher DPOAE amplitudes than the left non-tinnitus ear across most of the frequency range (988-11,429 Hz), suggesting preserved or even enhanced OHC function in the tinnitus ear. In contrast, the left tinnitus ear showed amplitudes that were comparable to or slightly greater than those of the right non-tinnitus ear, particularly at mid frequencies. However, paired-samples t-tests conducted across frequencies revealed no statistically significant differences between the groups (left tinnitus vs. right non-tinnitus: $t(11) = 0.71$, $p = .494$; right tinnitus vs. left non-tinnitus: $t(11) = -0.42$, $p = .683$). These findings suggest that while subtle amplitude differences are observable, they do not reach statistical significance, and thus may reflect either limited sample power or underlying heterogeneity in the cochlear involvement of tinnitus across ears.

Figure 12

Comparison of mean DPOAE amplitudes between tinnitus and non-tinnitus ears in participants with perceived unilateral tinnitus.



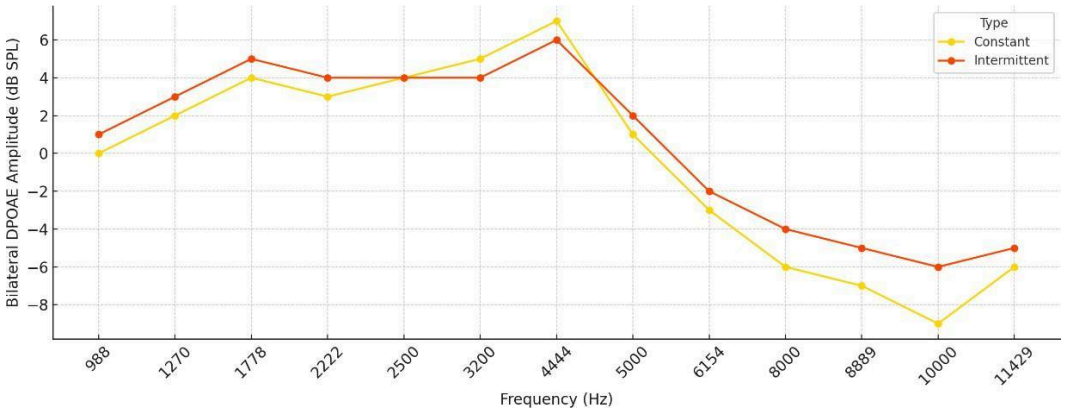
4.6.2 Comparison of Bilateral DPOAE Amplitudes by Tinnitus Type

To evaluate whether the temporal pattern of tinnitus, constant versus intermittent, is associated with differences in OHC function, bilateral mean DPOAE amplitudes were calculated by averaging left and right ear values at each frequency. These bilateral values were then compared across the two types of tinnitus.

As illustrated in Figure 13, both groups followed a broadly similar frequency response pattern, with amplitudes peaking in the mid-frequency region and declining at higher frequencies. Although the intermittent group appeared to have slightly higher mean amplitudes at 2500-5000 Hz, one-way ANOVA tests conducted at each frequency revealed no statistically significant differences between groups (all $p > 0.05$).

Figure 13

Effect of Latency of Tinnitus on DPOAE amplitudes.



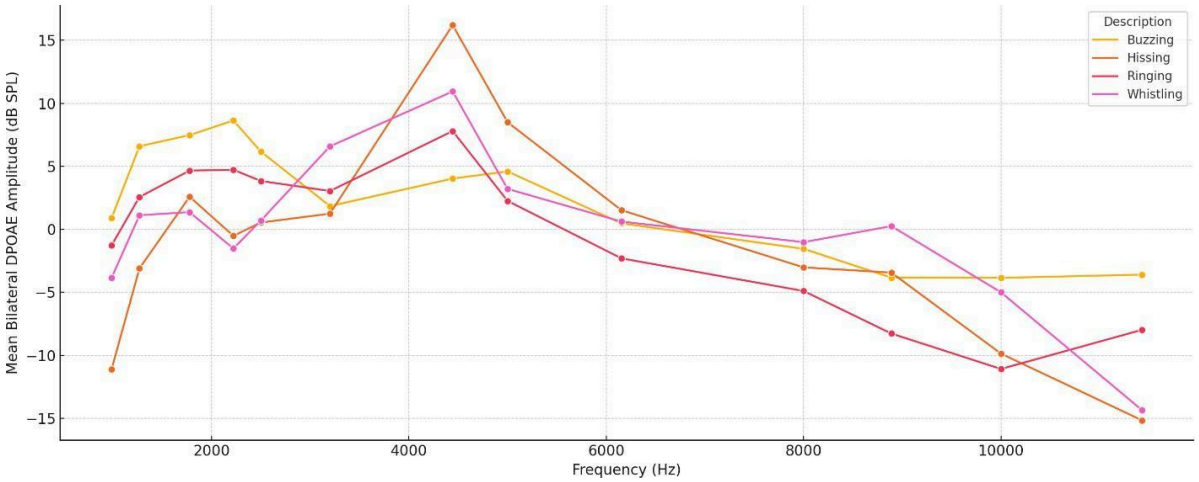
4.6.3 Bilateral DPOAE Amplitudes by Tinnitus Sound Description

To explore whether the perceived quality of tinnitus sound (referring to ringing, buzzing, hissing, or whistling) corresponds to specific patterns of OHC function, bilateral DPOAE amplitudes were compared across frequency for participants grouped by their reported tinnitus sound description.

As shown in Figure 14, distinct amplitude profiles were observed between sound types. The buzzing group consistently exhibited the highest mean DPOAE amplitudes across most frequencies, particularly in the mid-frequency range (1270-4444 Hz). In contrast, the hissing and whistling groups showed substantially lower amplitudes at both low (988-1778 Hz) and high frequencies (8000-11429 Hz), suggesting more widespread cochlear dysfunction. The ringing group displayed intermediate amplitude levels, with a steady decline at higher frequencies. However, these findings are exploratory and should be interpreted cautiously due to potential overlap and small subgroup sizes.

Figure 14

Perceived tinnitus sound and DPOAE amplitudes.



4.7 Impact of Noise Exposure on DPOAEs

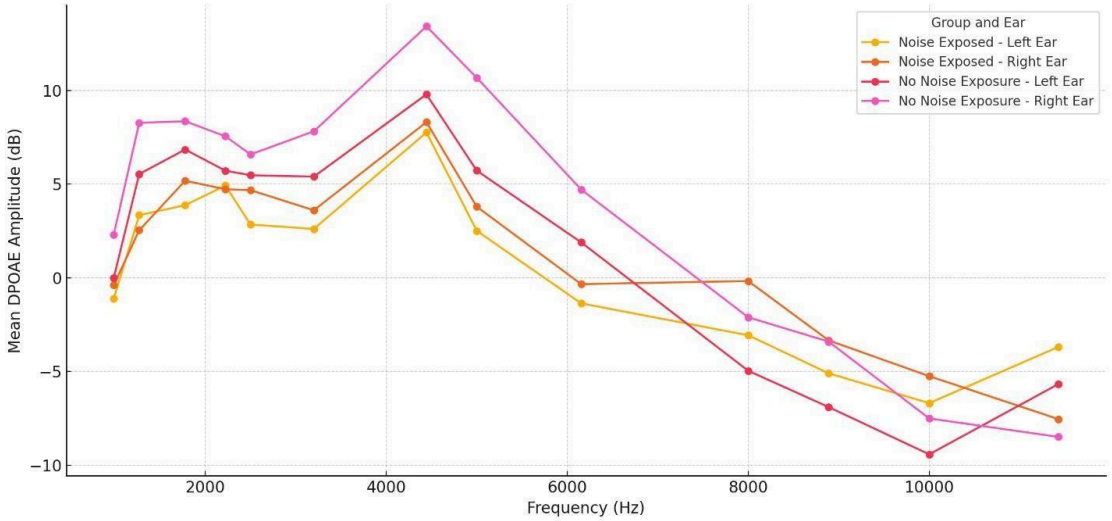
A line graph was generated to compare the mean amplitudes across frequencies ranging from 988 Hz to 12,000 Hz for both ears in two participant groups: those with self-reported recreational noise exposure and those with no history of noise exposure. The graph displays four distinct lines, representing the left and right ears in each group: Noise-Exposed Left Ear, Noise-Exposed Right Ear, Non-Exposed Left Ear, and Non-Exposed Right Ear. This visualization reveals a consistent pattern where individuals with no history of noise exposure generally exhibited higher DPOAE amplitudes across most frequencies compared to their noise-exposed counterparts.

This trend was especially notable in the higher frequencies (above 4000 Hz), where cochlear damage due to noise exposure typically manifests first. Additionally, the right ear in the non-exposed group often demonstrated the highest amplitudes, suggesting a possible ear asymmetry or increased susceptibility in one ear over the other. Conversely, the noise-exposed group displayed reduced amplitudes, particularly in the higher-frequency regions, which may reflect subtle OHC dysfunction consistent with early noise-induced cochlear changes. Overall, this analysis supports the hypothesis that even in individuals with clinically

'normal' hearing thresholds, noise exposure may diminish cochlear responsiveness, especially at high frequencies, and highlights the sensitivity of DPOAEs in detecting early cochlear changes (see Figure 15)

Figure 15

Impact of self- reported recreational noise exposure on mean DPOAEs.



4.7.1. Statistical Comparison of Noise Exposure on DPOAE Amplitudes

To determine whether noise exposure was associated with changes in cochlear function, Mann-Whitney U tests were conducted to compare DPOAE amplitudes between noise-exposed and non-exposed individuals across frequencies ranging from 988 Hz to 12,000 Hz, for both the left and right ears. This non-parametric test was chosen due to the non-normal distribution of amplitude data.

A total of 24 comparisons (12 frequencies × 2 ears) were performed. To control the risk of false positives due to multiple comparisons, a Bonferroni correction was applied. While several uncorrected *p*-values were below 0.05, notably at 1270 Hz in the right ear (p = 0.029), none remained statistically significant after correction. These results suggest that, although there may be trends toward reduced DPOAE amplitudes in noise-exposed

individuals, especially in the higher frequencies and right ear, these differences did not reach statistical significance in this sample.

4.8 Age and its effect on DPOAE amplitudes

To examine potential age-related changes in cochlear function, DPOAE amplitudes were analysed across four age groups: 18-24, 25-30, 31-35, and 36-40 years. Mean amplitudes were calculated for each frequency within these age bands, and a one-way ANOVA was conducted to assess statistical differences. Across the full range of frequencies (988-11429 Hz), no statistically significant differences were observed between age groups (all p-values > 0.05).

Despite the lack of statistical significance, a general trend was observed: participants in the 25-30 age group consistently exhibited the highest DPOAE amplitudes, particularly in the mid-frequency range (1778-4444 Hz), in contrast, the 36-40 group showed slightly reduced amplitudes, especially at higher frequencies.

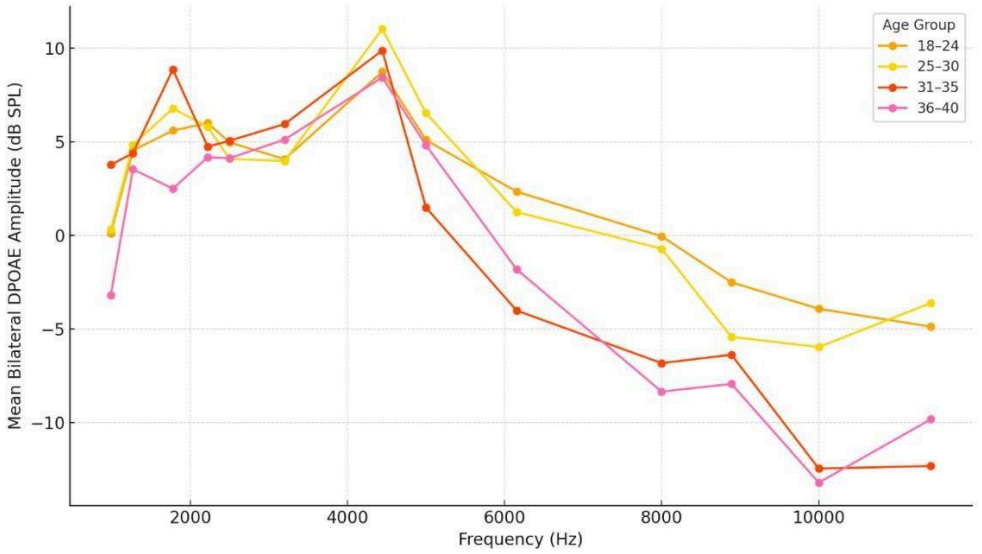
Figure 16 visualizes these patterns, showing that while DPOAE amplitudes decline slightly with age, the variation was not sufficient to reach statistical significance within the sampled age range. These findings suggest that within early adulthood, cochlear function as assessed by DPOAEs remains relatively stable, with only subtle age-related trends beginning to emerge around age 35-40.

To investigate whether age influences OHC function, bilateral mean DPOAE amplitudes were calculated by averaging left and right ear responses at each frequency for all participants. These values were then analysed across four age groups (18-24, 25-30, 31-35, and 36-40 years). A one-way ANOVA revealed no statistically significant differences in DPOAE amplitudes across age groups at any of the tested frequencies (p > 0.05). As shown in Figure 16, all age groups followed a similar trend across the frequency range, with a

general decline in amplitude at higher frequencies. The 25-30 group displayed slightly elevated amplitudes in the mid-frequency region, though this difference did not reach statistical significance. These findings suggest that cochlear function, as assessed through DPOAE amplitude, remains relatively stable throughout early adulthood, with no measurable deterioration in outer hair cell response detectable by this method between ages 18 and 40.

Figure 16

Age and its effect on mean bilateral DPOAE amplitudes.



4.9 Conclusion

The findings presented in this chapter offer a comprehensive examination of cochlear OHC function in individuals with and without tinnitus using DPOAEs. Across multiple analyses, a consistent trend emerged in which tinnitus participants demonstrated reduced DPOAE amplitudes at high frequencies (≥6154 Hz), despite having clinically ‘normal’ hearing thresholds. While no significant differences were observed at low to mid frequencies, the steep decline in emission amplitudes at higher frequencies and the significant Group × Frequency interaction suggest frequency-specific cochlear dysfunction in the tinnitus group.

Neither tinnitus laterality nor latency showed a measurable impact on DPOAE amplitude patterns. Age also did not significantly influence OHC function within the tested adult range (19-40 years), although slight amplitude reductions were noted in participants aged 36-40.

Exploratory findings revealed novel patterns related to the perceived quality of tinnitus. Participants describing their tinnitus as buzzing had higher DPOAE amplitudes, whereas those reporting hissing or whistling exhibited more pronounced amplitude reductions, particularly in low and high frequency regions.

In the following chapter, these outcomes will be interpreted in the context of existing research, with a focus on their theoretical and clinical implications.

Chapter 5: Discussion

This chapter comprehensively discusses the research questions by evaluating the findings reported in the preceding chapter, comparing them to the current body of literature and other published studies. This discussion provides a thorough evaluation of the data by combining the findings with existing research. It emphasizes the similarities and differences between the present data and past studies. This comparative method not only places the study in its broader perspective but also highlights its contributions and consequences of its findings.

5.1 Research Questions

The research questions outlined in Chapter 2 were designed to explore various aspects of High Frequency Distortion Product Otoacoustic Emissions (HF-DPOAEs) amplitudes in individuals with tinnitus. The research questions targeted are:

1. Do HF-DPOAE amplitudes differ significantly between individuals with tinnitus and those without, despite clinically ‘normal’ pure-tone audiograms?
2. Is there a correlation between reduced DPOAE amplitudes and the subjective impact of tinnitus?
3. Can HF- DPOAEs (>8000 Hz) reliably differentiate between tinnitus and non-tinnitus individuals?
4. Are specific characteristics of tinnitus, such as sound quality, laterality, and constancy, associated with distinct DPOAE profiles?
5. Is there a difference in DPOAE amplitudes between tinnitus and non-tinnitus individuals with a history of recreational noise exposure?
6. What role do age-related changes play in the interpretation of DPOAE profiles in adults with tinnitus?

In answering these research objectives, this chapter provides an exploratory assessment of the importance of the application of high frequency DPOAEs in the assessment of individuals with tinnitus with within 'normal' hearing thresholds.

5.2 Research Question 1: Do high-frequency DPOAE amplitudes differ significantly between individuals with tinnitus and those without, despite clinically 'normal' pure- tone audiograms?

5.2.1 Audiometric Threshold Findings within groups

The observed elevation in mean pure-tone audiometric (PTA) thresholds in the tinnitus group, particularly at high frequencies, aligns with previous findings that suggest subtle cochlear deficits may exist even in individuals with clinically 'normal' hearing. Notably, a statistically significant difference was identified at 6000 Hz in the left ear (p = .041) between the tinnitus and control group, supporting the notion that high-frequency regions of the cochlea may be disproportionately affected in individuals with tinnitus. This is consistent with studies proposing that high-frequency hearing loss, even when subclinical, may serve as an early marker of cochlear dysfunction and be implicated in tinnitus generation mechanisms (Liberman & Kujawa, 2017; Schaette & McAlpine, 2011).

Moreover, the greater inter-individual variability observed in the tinnitus group, particularly at 6000 Hz and 8000 Hz, though not statistically significant, suggests increased heterogeneity in high-frequency auditory sensitivity. This variability may reflect individual differences in noise exposure history, early-stage outer hair cell (OHC) damage, or other peripheral auditory pathologies that are not detectable through standard threshold-based audiometry alone (Bramhall et al., 2019). Such findings further support the hypothesis that tinnitus may, in some cases, be a manifestation of hidden hearing loss (HHL), where

synaptopathy or minor OHC dysfunction contributes to auditory perceptual anomalies despite clinically 'normal' audiograms (Bharadwaj et al., 2014).

Taken together, these results highlight the importance of supplementing conventional audiometry with more sensitive diagnostic measures, such as otoacoustic emissions (OAEs), to detect early or subclinical cochlear changes in tinnitus populations. The patterns observed in this study underscore the need to re-evaluate what constitutes "'normal' hearing" in the context of tinnitus and high-frequency cochlear vulnerability.

These results highlight the limitations of relying solely on standard audiometry when assessing auditory function in individuals with tinnitus. Despite thresholds falling within clinically 'normal' ranges, subtle high-frequency deficits and increased inter-individual variability suggest the possibility of underlying cochlear changes not captured by conventional testing.

In light of these findings, this study explored a series of focused research questions aimed at evaluating whether otoacoustic emissions, particularly at high frequencies, can offer additional diagnostic insight into tinnitus-related cochlear dysfunction.

5.2.2 DPOAE characteristics and differences between groups

The results of the current study offer compelling evidence that HF-DPOAEs may serve as a sensitive, objective indicator of subclinical cochlear dysfunction in individuals experiencing tinnitus, even when conventional audiometric thresholds fall within clinically 'normal' limits. This finding addresses one of the enduring challenges in audiology; identifying physiological correlates of tinnitus in patients who present with conventionally acceptable pure-tone audiograms (PTA).

Specifically, the tinnitus group exhibited reduced DPOAE amplitudes at several high-frequency points ≥ 6154 Hz. These findings mirror prior research by Ami et al., 2024 Jedrzejczak et al. (2023) and Ueberfuhr et al. (2020), who reported high-frequency OHC deficits in tinnitus patients without measurable hearing loss, reinforcing the notion that basal cochlear regions may be disproportionately affected in this population. Similarly, Fabijańska et al. (2012) found that patients with unilateral tinnitus and 'normal' hearing showed significantly lower DPOAE amplitudes and poorer extended high-frequency (EHF) thresholds than controls.

This is in line with the discordant damage theory, which posits that disproportionate damage to OHCs relative to inner hair cells (IHCs) can lead to aberrant neural activity and the perception of tinnitus (Jastreboff, 1990; Sziklai, 2004). Notably, while both groups exhibited similar patterns in the mid-frequency range (1270-2500 Hz), the control group consistently demonstrated higher emission amplitudes across nearly all frequencies, indicating better-preserved cochlear function.

In addition to assessing statistical significance, the present study incorporated Cohen's *d* to evaluate the effect sizes of group differences in DPOAE amplitudes. This measure offers a valuable perspective on the magnitude of observed differences, independent of sample size. Several frequencies, particularly in the right ear, demonstrated large effect sizes despite non-significant *p*-values. For example, at 988 Hz and 1270 Hz, Cohen's *d* values reached -0.89 and -0.82, respectively, indicating substantial reductions in emission amplitudes in the tinnitus group. These findings suggest that some group differences, while not statistically significant, may still hold clinical relevance and reflect meaningful deviations in cochlear function. Given the relatively small sample size and variability inherent in OAE testing, effect sizes provide an important complement to traditional significance testing. This

highlights the need for a detailed interpretation of results, where both statistical outcomes and effect sizes are jointly considered to better understand the presence and extent of subclinical cochlear dysfunction in individuals with tinnitus. The integration of effect size metrics is therefore particularly valuable in auditory research, where subtle physiological changes may otherwise go undetected through *p*-values alone.

The observed frequency-specific decline in emission amplitude aligns with the theoretical framework of HHL, which posits that auditory deficits, most often linked to synaptic or OHC dysfunction, can be present even in the absence of threshold elevation (Liberman, 2017; Schaette & McAlpine, 2011). Within this context, HF- DPOAEs have emerged as a particularly valuable tool, capable of detecting subtle cochlear alterations that may represent early manifestations of pathology in individuals with tinnitus (Bharadwaj et al., 2014; Zhao et al., 2014).

The absence of significant differences at 10000 Hz ($p = 0.081$) in the left ear, despite a similar trend, could reflect increased variability or reduced test sensitivity at the upper edge of measurable emissions. Together, these results highlight that subtle changes in OHC function may be more readily detectable in the high-frequency domain among individuals experiencing tinnitus, providing potential peripheral markers of early cochlear alterations.

Independent-sample *t*-tests conducted for each ear further confirmed these trends, revealing significant group differences across multiple frequencies. In the right ear, the tinnitus group exhibited significantly reduced amplitudes at 988 Hz, 4444 Hz, and 5000 Hz, while in the left ear, the most notable reduction was at 8000 Hz. While the most robust effects were seen at higher frequencies, low-frequency reductions may reflect more global OHC dysfunction or measurement variability and deserve further investigation. These findings reinforce the notion that even small deviations in cochlear output may signal

underlying OHC disruption, aligning with studies that have demonstrated altered DPOAEs in tinnitus patients despite 'normal' hearing thresholds (Fabijańska et al., 2012; Modh et al., 2014; Ami et al., 2008).

Additionally, the negative DPOAE amplitudes observed at 988 Hz in the tinnitus group may suggest absent or compromised emissions at very low frequencies. While variability in low-frequency DPOAEs can be influenced by middle ear mechanics and noise floor limitations, this trend still warrants attention as it may signal broader cochlear instability (Hunter, 2020).

Collectively, these findings support the emerging view that HF-DPOAEs can serve as sensitive indicators of HHL and early cochlear dysfunction in tinnitus populations (Jedrzejczak et al., 2022; Schaette & McAlpine, 2011). They also highlight the limitations of relying solely on pure-tone thresholds in tinnitus assessment and the clinical relevance of including objective measures like DPOAEs to uncover subtle auditory pathologies (Marshall et al., 2001).

To further explore the pattern of DPOAE amplitude variation between groups and across frequencies, a two-way mixed ANOVA was conducted. This analysis revealed a statistically significant main effect of Group, $F(1, 975) = 9.77$, $p = .0018$, confirming that participants with tinnitus exhibited lower overall DPOAE amplitudes compared to controls across all frequencies. This group-level effect aligns with the earlier frequency-specific findings and supports the hypothesis that cochlear OHC dysfunction, although subclinical, is measurably greater in the tinnitus population (Jedrzejczak et al., 2023; Ueberfuhr et al., 2020).

While the ANOVA revealed a general group-level effect, the linear mixed-effects model further demonstrated a frequency-specific interaction, suggesting a more pronounced

decline in DPOAE amplitude with increasing frequency in the tinnitus group. This finding supports the hypothesis of frequency-dependent OHC dysfunction and adds detail to the ANOVA result, indicating that not only are DPOAEs lower overall in individuals with tinnitus, but the slope of decline across frequency is steeper. Such a pattern may reflect subtle basal cochlear vulnerability or early-onset damage that preferentially affects high-frequency regions (Liberman, 2017; Guest et al., 2022).

The absence of a significant main effect of Group (β = -0.75, p = .643) indicates that when DPOAE amplitudes are averaged across all tested frequencies, the overall difference between tinnitus and control participants is not large enough to reach statistical significance. This aligns with prior literature suggesting that cochlear damage in tinnitus may be subtle, localized, or limited to specific frequency regions (Karimiani et al., 2024; Fabijańska et al., 2012). Importantly, the significant interaction term (β = -0.001, p = .004) underscores that this group difference is not uniform across frequencies but instead varies systematically with increasing frequency.

This pattern yet again supports the hypothesis that OHC dysfunction in tinnitus is more pronounced at higher frequencies; a finding echoed in numerous studies that report reduced DPOAE amplitudes above 6000 Hz in tinnitus patients (Shiomi et al., 1997; Zhao et al., 2014). The steeper amplitude decline observed in the tinnitus group may reflect early-stage or localized cochlear pathology that escapes detection through conventional audiometry but is identifiable via DPOAE measures. This is consistent with the concept of HHL or subclinical OHC damage, which is not reflected in pure-tone thresholds but may nonetheless contribute to aberrant auditory perception such as tinnitus (Schaette & McAlpine, 2011; Emadi et al., 2024).

From a physiological perspective, this frequency-specific vulnerability may be attributed to the basal turn of the cochlea, responsible for encoding high frequencies, being more susceptible to noise exposure and age-related changes (Granjeiro et al., 2008). The discordant damage theory also posits that selective OHC damage in these regions can disrupt the balance of afferent input from IHCs, resulting in aberrant activity interpreted centrally as tinnitus (Jastreboff, 1990; Hall, 2000).

Clinically, these findings reinforce the diagnostic utility of frequency-resolved DPOAE analysis in tinnitus assessment, especially in individuals with 'normal' hearing thresholds. The high sensitivity of DPOAEs to early OHC dysfunction may aid in identifying candidates for early intervention or monitoring disease progression. Moreover, the observed interaction lends further support to incorporating HF-DPOAE (>8 kHz) testing, which may capture subtle cochlear changes undetectable at conventional frequencies (Jedrzejczak et al., 2022; Dreisbach & Siegel, 2016).

A robust main effect of Frequency was also observed, $F(12, 975) = 45.08$, $p < .001$, indicating a consistent decline in DPOAE amplitude with increasing frequency stimulus across both groups. This frequency-dependent pattern is expected given the anatomical and physiological layout of the cochlea, where high-frequency regions in the basal turn are typically more susceptible to noise-induced or age-related damage (Liberman & Kujawa, 2017; Fabijańska et al., 2012). The amplitude reduction across ascending frequencies reflects well-documented cochlear mechanics, particularly the increased vulnerability of basal OHCs.

Interestingly, the Group × Frequency interaction was not statistically significant, $F(12, 975) = 0.99$, $p = .452$. This suggests that while overall DPOAE amplitudes were lower in the tinnitus group, the shape of the amplitude profile across frequencies was largely similar across groups. Therefore, tinnitus appears to be associated with a uniform attenuation of

OHC function, rather than a distortion of the cochlear tonotopic response. This implies that cochlear dysfunction in tinnitus may reflect a generalized reduction in cochlear output rather than sharply localized frequency-specific deficits. Such a pattern is consistent with theories proposing diffuse OHC degradation, potentially driven by synaptic, metabolic, or efferent mechanisms that subtly impair cochlear function across the frequency range (Liberman, 2017; Jedrzejczak et al., 2022). However, the absence of a statistically significant interaction does not negate the clinical relevance of frequency-level effects. Visual inspection of the data and direct comparisons at individual frequencies indicated that DPOAE reductions were especially pronounced at high-frequency sites above 6154 Hz. This trend aligns with previous reports of basal cochlear vulnerability in tinnitus patients and supports the idea that high- frequency cochlear regions are particularly susceptible to early-stage dysfunction (Fabijańska et al., 2012; Jedrzejczak et al., 2023). At higher frequencies, the tinnitus group's amplitudes tended to decline further, with some values dipping below 0 dB SPL, suggesting reduced cochlear output or subtle outer hair cell dysfunction. These findings underscore the importance of analysing DPOAE responses at individual frequency points rather than relying solely on global mean amplitudes. Even when statistical interactions are absent, frequency-specific analyses can reveal subtle but clinically meaningful patterns. The current results suggest that despite 'normal' audiometric thresholds, individuals with tinnitus may experience disproportionate reductions in OHC output at higher frequencies, reinforcing the diagnostic utility of HF-DPOAEs in uncovering subclinical cochlear pathology. These trends may reflect early-stage cochlear changes potentially linked to noise exposure, subclinical OHC dysfunction, or other contributing factors affecting auditory function at higher frequencies (Guest et al., 2022; Fernandez et al., 2020).

The present study's identification of HF- DPOAE amplitude reductions in the tinnitus group aligns with findings from Jedrzejczak et al. (2023) and Ueberfuhr et al. (2020), who

reported similar subclinical deficits in high-frequency cochlear function. The control group consistently exhibited higher DPOAE amplitudes across most frequencies in both ears, suggesting better-preserved OHC function. These studies, along with Fabijańska et al. (2012), emphasize the basal cochlear turn as particularly vulnerable in tinnitus, often revealing OHC damage missed by standard pure-tone audiometry.

The observed frequency-specific decline in DPOAE amplitude aligns with the "hidden hearing loss" framework, wherein auditory deficits exist despite 'normal' audiograms, often due to synaptic or hair cell dysfunction not captured by threshold-based tests (Liberman, 2017; Zhao et al., 2014; Schaette & McAlpine, 2011). In this context, high-frequency DPOAEs emerge as particularly valuable, as they are capable of detecting subtle cochlear changes that precede overt hearing loss, thereby offering a window into the early manifestations of cochlear pathology in individuals with tinnitus.

It is important to contextualize these findings within the broader scientific discourse, which acknowledges variability in DPOAE outcomes across tinnitus studies. While the majority of literature supports the presence of reduced DPOAEs in tinnitus, some studies, such as Sztuka et al., 2010; Gouveris et al., 2005) have reported elevated emissions, hypothesizing compensatory OHC hyperactivity or reduced efferent suppression. However, such contradictory findings often arise from differences in stimulus parameters, frequency resolution, or participant selection criteria (Jedrzejczak et al., 2022). The current study controlled for many of these variables and focused specifically on high-frequency emissions, a range that has demonstrated higher sensitivity in detecting early-stage cochlear pathology (Job et al., 2007).

These findings provide important evidence that high-frequency cochlear dysfunction is more pronounced in individuals with tinnitus. They also emphasize the value of frequency-

specific analysis of OAEs, rather than relying solely on overall mean amplitude levels, in uncovering subtle cochlear impairments associated with tinnitus pathology.

5.3 Research Question 2: Is there a correlation between reduced DPOAE amplitudes and the severity of subjective tinnitus?

The potential relationship between DPOAE amplitude and subjective tinnitus impact remains a complex and unresolved issue within auditory science. In this study, although a clear frequency-dependent decline in DPOAE amplitudes was observed in the tinnitus group, particularly at higher frequencies (≥8046 Hz), this decline did not demonstrate a statistically significant correlation with participants' reported tinnitus impact. While seemingly inconclusive, this outcome aligns with a growing body of literature suggesting that the association between peripheral cochlear function and tinnitus-related distress is not necessarily linear or direct.

The negative correlation observed between HF- DPOAE amplitude and tinnitus severity ($\rho = -0.26$) supports the hypothesis that increased cochlear damage is associated with more distressing tinnitus experiences (Schaette & McAlpine, 2011). Though the correlation did not reach statistical significance, the moderate effect size suggests potential clinical relevance and warrants replication in larger, more balanced cohorts. In contrast, the positive correlations at low and mid frequencies were unexpected. These may reflect compensatory mechanisms, such as increased efferent feedback, or be influenced by measurement of variability. Such findings are in line with Sztuka et al.'s (2010) elevated DPOAE theory in early-stage tinnitus, where central reorganization has not yet suppressed peripheral responses.

From a physiological standpoint, OHCs in the basal cochlear region are more vulnerable to damage from noise exposure and aging, typically leading to attenuated DPOAE amplitudes at higher frequencies (Rajan, 2001; Malviya & Saravanan, 2024). Numerous

studies have shown that reductions in DPOAE amplitude, especially within the 4-10 kHz range, are more frequent in tinnitus patients than in controls (Modh et al., 2014; Fabijańska et al., 2012; Jedrzejczak et al., 2023). This study extends these observations to even higher frequencies, with significant amplitude reductions noted at 10 kHz in the tinnitus group. These findings support a frequency-dependent pattern of cochlear dysfunction associated with tinnitus presence, even if not directly linked to perceived severity.

When tinnitus severity, measured using the 4C-TQ, was correlated with DPOAE amplitudes across individual frequencies, no strong associations emerged. This dissociation between objective and subjective measures is consistent with prior findings by Shekhawat et al. (2014), who reported poor alignment between DPOAE deficits and self-reported tinnitus pitch or loudness. Similarly, Husain (2013) emphasized that tinnitus presence and intensity often do not correspond directly to the degree of measurable cochlear impairment, especially in patients with clinically ‘normal’ audiograms.

Several plausible explanations may account for this weak association. First, the neurophysiological model of tinnitus proposed by Jastreboff and Hazell (1990) suggests that tinnitus distress is largely shaped by central mechanisms, including the limbic and autonomic systems, rather than being proportionally driven by peripheral dysfunction. Neuroimaging studies further support this model, demonstrating the involvement of emotional regulation centres such as the ventromedial prefrontal cortex and nucleus accumbens in tinnitus persistence and severity (Leaver et al., 2011; Rauschecker, 2024).

Second, maladaptive plasticity in the auditory cortex may lead to an overrepresentation of phantom signals following cochlear damage. In this scenario, the degree of peripheral dysfunction acts as a trigger for tinnitus onset but does not directly govern its perceived severity, this instead depends on individual differences in central gain,

attentional salience, and emotional reactivity (Yang et al., 2011; Schaette & McAlpine, 2011).

Third, methodological factors may obscure accurate physiological-perceptual relationships. Tinnitus severity is a multidimensional construct, encompassing perceptual, emotional, and functional dimensions (Henry et al., 2014). While instruments like the 4C-TQ attempt to quantify this complexity, they may not correlate cleanly with single physiological markers like DPOAE amplitude. Additionally, DPOAEs are influenced by extraneous variables, such as ear canal acoustics, middle ear status, and noise floor, which introduce variability and reduce measurement sensitivity (Kemp, 2008; Boothalingam & Purcell, 2022).

Despite these limitations, the non-significant trends in this study align with other reports suggesting a weak but directionally consistent association between reduced high-frequency cochlear output and greater tinnitus impact. For example, Ami et al. (2024) similarly observed a negative correlation between high-frequency DPOAEs and TFI scores, although their results, like the current study, were constrained by sample size.

Taken together, these findings emphasize the importance of interpreting DPOAE-severity associations within a broader biopsychosocial model. They also reinforce the need for multimodal approaches, combining objective cochlear measures with cortical imaging and comprehensive patient-reported outcomes, to elucidate the complex relationship more fully between peripheral damage and tinnitus distress.

5.4 Research Question 3: Can high-frequency DPOAEs (>8000 Hz) reliably differentiate between tinnitus and non-tinnitus individuals?

A central aim of the present study was to evaluate whether HF-DPOAEs could serve as a clinically meaningful supplementary diagnostic tool for tinnitus, particularly in

individuals with ‘normal’ audiograms. This objective is anchored in growing evidence suggesting that conventional PTA, typically limited to frequencies up to 8000 Hz, may fail to detect subtle cochlear pathology, especially in the basal turn of the cochlea where high-frequency sounds are encoded (Liberman, 2017; Fabijańska et al., 2012; Ueberfuhr et al., 2020). The OHCs, which generate DPOAEs, are especially vulnerable to damage from noise exposure and aging (Rajan, 2001; Salvi et al., 2000), often deteriorating before any detectable threshold shifts on standard audiometry. This diagnostic limitation has led to increased interest in HF-DPOAEs as a tool to uncover HHL and subclinical cochlear dysfunction that may underlie tinnitus (Jastreboff, 2004; Eggermont & Roberts, 2015).

In line with this theoretical framework, the present study assessed DPOAE amplitudes across a wide frequency range in participants with and without tinnitus who presented with clinically ‘normal’ audiograms. Results revealed consistent reductions in DPOAE amplitudes among tinnitus participants across both ears, with the most pronounced differences occurring in the high-frequency range (≥5000 Hz). As previously demonstrated in Objective 1, group comparisons at specific frequencies (e.g., 988 Hz and 8000 Hz) yielded large effect sizes (Cohen’s d = -0.89 and -0.87 for the right and left ears, respectively), indicating a clinically relevant reduction in cochlear output in the tinnitus group.

To enhance clinical interpretability and reduce the risk of multiple comparisons, DPOAE amplitudes were also averaged into low (988-2222 Hz), mid (2500-4444 Hz), and high (5000-11429 Hz) frequency bands. Statistically significant group differences were identified in the mid-frequency band of the right ear (p = .0099) and the high-frequency band of the left ear (p = .0087). These results indicate that tinnitus is associated with reduced OHC function in frequency-specific regions of the cochlea, reinforcing the hypothesis of peripheral auditory involvement in tinnitus perception. Additionally, a trend toward significance was

observed in the low-frequency band of the right ear (p = .0812), which may point to emerging subclinical dysfunction not yet detectable via threshold shifts.

As illustrated in Figure 11, the tinnitus group consistently showed lower band-averaged DPOAE amplitudes across all frequency ranges and both ears, with the greatest disparities observed in the high-frequency domain. These patterns align with the discordant damage theory (Jastreboff, 1990; 2004), which proposes that partial loss of OHC function—especially in the basal cochlea, can disrupt neural balance and generate the perception of sound. Importantly, this theory also posits that up to 30% OHC loss can exist without elevating hearing thresholds, supporting the use of DPOAEs as a sensitive early marker of cochlear dysfunction.

These findings are consistent with prior literature reporting DPOAE reductions in tinnitus patients with 'normal' hearing (Modh et al., 2014; Dall'Igna et al., 2015), and they corroborate recent studies such as those by Ami et al. (2024), Emadi et al. (2024), and Abo Jamous et al. (2024), which have highlighted the diagnostic value of high-frequency emissions. While DPOAEs should not be interpreted in isolation, their integration into a broader tinnitus assessment battery. Alongside extended high-frequency audiometry, auditory brainstem response testing, and self-report questionnaires, can meaningfully improve diagnostic precision and contribute to individualized management plans (Shoushtarian et al., 2020).

In conclusion, the present findings support the clinical utility of DPOAEs for detecting frequency-specific cochlear changes in individuals with tinnitus and 'normal' hearing thresholds. The significant reductions observed in mid- and high-frequency bands reinforce the role of OHC dysfunction in the pathophysiology of tinnitus and highlight the importance of including DPOAEs in comprehensive tinnitus diagnostic protocols.

5.5 Research Question 4: Are specific characteristics of tinnitus, such as sound quality, laterality, and constancy, associated with distinct DPOAE profiles?

This section investigates whether subjective features of tinnitus, namely sound quality (tonal vs. noise-like), laterality (unilateral vs. bilateral), and temporal constancy (intermittent vs. continuous), correspond to measurable differences in cochlear function, as assessed through DPOAEs. While no statistically significant differences were observed across these subgroups, descriptive patterns offer insight into the complex and heterogeneous relationship between tinnitus perception and OHC integrity. These findings contribute to the growing recognition that subjective tinnitus profiles may not always map directly onto peripheral auditory dysfunction, highlighting the need for integrative models that consider both cochlear and central auditory processes.

5.5.1 Tinnitus Laterality and Interaural DPOAE Asymmetries

Unilateral tinnitus presents a clinically valuable model for investigating localized cochlear pathology, particularly when conventional audiometric thresholds are symmetric across ears. In such cases, intra-individual comparisons, between the tinnitus-affected and non-affected ear, offer a controlled approach to exploring potential subclinical cochlear asymmetries, most notably those associated with outer hair cell (OHC) dysfunction.

To explore whether tinnitus perception in one ear corresponds to measurable peripheral dysfunction, this study conducted intra-individual comparisons of DPOAE amplitudes between tinnitus and non-tinnitus ears in participants with unilateral tinnitus. Despite initial expectations that the tinnitus ear would exhibit reduced cochlear output, paired-samples *t*-tests revealed no statistically significant differences in mean DPOAE amplitudes between ears, regardless of whether tinnitus was perceived on the left or right side. These findings align with previous research by Guest et al. (2017) and Ueberfuhr et al.

(2020), who also reported minimal interaural differences in OAEs among tinnitus patients with ‘normal’ hearing, suggesting that measurable asymmetries in OHC function may not be a consistent feature of unilateral tinnitus.

Further intergroup comparisons between the tinnitus ear of one subgroup and the non-tinnitus ear of the contralateral subgroup revealed subtle trends. The right tinnitus ear consistently displayed higher amplitudes than the left non-tinnitus ear across the frequency range, while the left tinnitus ear showed amplitudes roughly equivalent to or slightly higher than the right non-tinnitus ear. However, these lateral differences did not reach statistical significance ($p = .494$ and $p = .683$), and may reflect either limited statistical power due to small subgroup sizes or underlying heterogeneity in the peripheral involvement of tinnitus.

Additionally, the possibility that unilateral tinnitus arises from central mechanisms rather than localized cochlear dysfunction must be considered. Neuroimaging studies (Yang et al., 2011; Schaette & McAlpine, 2011) have shown that asymmetric central auditory processing, rather than peripheral asymmetry, can drive tinnitus lateralization. This is echoed in Jastreboff’s neurophysiological model, which posits that central gain, limbic system engagement, and efferent feedback can shape the percept and lateralization of tinnitus independently of cochlear status.

Notably, some studies have identified small but consistent cochlear asymmetries corresponding to tinnitus laterality. Fabijańska et al. (2012) and Park et al. (2012) reported reduced DPOAE amplitudes in the tinnitus ear, particularly in the 3-6 kHz range, suggesting region-specific OHC compromise. Similarly, Keppler et al. (2010) and Shi et al. (2018) observed lateralized DPOAE reductions that aligned with the tinnitus percept, while Knudson et al. (2014) suggested that such asymmetries may reflect interactions between peripheral damage and central compensatory mechanisms. These findings are consistent with the

discordant damage hypothesis (Jastreboff, 1990; 2004), which proposes that an imbalance between damaged OHCs and intact IHCs can generate aberrant neural activity that contributes to tinnitus.

Importantly, tinnitus laterality does not necessarily imply unilateral cochlear pathology. Animal and neuroimaging studies suggest that unilateral tinnitus can arise from symmetric peripheral input but asymmetric central processing, including cortical plasticity and altered gain (Schaette & McAlpine, 2011; Yang et al., 2011). Jastreboff's (1990) neurophysiological model also highlights the role of limbic and autonomic networks in shaping the percept and lateralization of tinnitus, even when peripheral findings are inconclusive.

Finally, cochlear efferent system dynamics may play a role. Asymmetric medial olivocochlear (MOC) reflex function could modulate OHC responsiveness and DPOAE amplitudes across ears, even in the absence of structural damage (Guinan, 2018; Boothalingam & Purcell, 2022). This aspect was not directly assessed in the present study but represents an important area for future research.

Taken together, these results suggest that cochlear asymmetry is not a universal hallmark of unilateral tinnitus. The lack of consistent DPOAE differences across ears may indicate that in some cases, tinnitus perception arises from central auditory processes or dynamic peripheral mechanisms not captured by OAE testing. This interpretation is supported by theories of central gain and maladaptive plasticity, which propose that central neural amplification can sustain tinnitus perception even in the absence of measurable cochlear asymmetry (Noreña & Eggermont, 2003; Sedley et al., 2016). Therefore, while lateralized OHC dysfunction may contribute to tinnitus in some individuals, the present

findings underscore the importance of considering both peripheral and central factors when evaluating tinnitus laterality.

5.5.2 Perceived Sound Quality: Tonal vs. Noise-Like Tinnitus

From a theoretical perspective, different tinnitus sound qualities are thought to reflect distinct underlying mechanisms. Tonal tinnitus is often linked to more focal cochlear damage, whereas noise-like tinnitus has been associated with diffuse peripheral dysfunction or central auditory dysregulation (Baguley, 2002; De Ridder et al., 2015). The discordant damage theory (Jastreboff, 1990) further posits that tonal tinnitus may emerge when OHCs are damaged while IHCs remain intact, leading to an imbalance in afferent signalling.

In this study, although no significant differences in DPOAE amplitudes were observed between tonal and noise-like tinnitus subgroups, participants with noise-like tinnitus exhibited a trend toward lower mean DPOAE amplitudes, especially in the high frequency range (≥8046 Hz). This pattern suggests a potential link between noise-like tinnitus and more widespread OHC dysfunction. These findings are consistent with Fabijańska et al. (2012), who reported more generalised DPOAE reductions in bilateral or noise-like tinnitus, in contrast to the more focal losses seen in unilateral tonal cases. Similarly, Jedrzejczak et al. (2023) observed that DPOAE profiles can vary within tinnitus populations, depending on subjective sound quality. Such as in Shiomi et al. (1997) identified DPOAE amplitude dips at frequencies corresponding to the pitch of tinnitus in the affected ear. *However, prior studies using different methodologies have reported contrasting results.*

5.5.3 Constancy of Tinnitus: Intermittent vs. Continuous Patterns

The temporal pattern of tinnitus perception, whether constant or intermittent, may reflect distinct underlying physiological mechanisms. Some theoretical models propose that persistent tinnitus results from ongoing cochlear dysfunction or sustained neural

hyperactivity, whereas intermittent tinnitus may involve more transient disturbances in auditory processing at either the peripheral or central level (Roberts et al., 2010; Eggermont & Roberts, 2015).

In the present study, bilateral DPOAE amplitudes were compared between participants with constant and intermittent tinnitus. Both groups exhibited similar frequency response patterns, with amplitude peaks in the mid-frequency range and progressive declines at higher frequencies. Although one-way ANOVA revealed no statistically significant differences between groups at any frequency (all $p > .05$), a small non-significant trend was noted; individuals with constant tinnitus tended to show slightly lower mean DPOAE amplitudes across frequencies than those with intermittent symptoms.

This trend may suggest that continuous tinnitus is associated with more stable and possibly chronic OHC dysfunction. In contrast, intermittent tinnitus could reflect fluctuating cochlear activity, transient efferent system modulation, or variability in central auditory gating (Rauschecker, 2024). These findings are consistent with Sztuka et al. (2010), who reported more pronounced and widespread DPOAE reductions in individuals with persistent tinnitus, particularly near tinnitus-matched frequencies.

However, overall, these findings suggest that the persistence or variability of tinnitus perception does not correspond to measurable differences in OHC function, at least as captured through these bilateral DPOAE measures. This aligns with prior research indicating that temporal patterns of tinnitus are more strongly associated with central auditory phenomena, such as thalamocortical dysrhythmia or maladaptive neural plasticity, than with peripheral dysfunction (De Ridder et al., 2011; Sedley et al., 2016).

Although the current study did not find statistically significant DPOAE differences based on tinnitus laterality, sound quality, or constancy, subtle patterns were observed that

align with theoretical models and previous research. These trends suggest that certain tinnitus subtypes—such as noise-like or persistent tinnitus—may be more closely associated with widespread OHC dysfunction, particularly at higher frequencies. Conversely, the absence of clear cochlear correlates in other subgroups reinforces the likelihood of central auditory involvement, especially in the case of unilateral or intermittent tinnitus.

These findings underscore the complexity of tinnitus and highlight the limitations of relying solely on peripheral measures like DPOAEs for characterizing subjective tinnitus profiles. Future research in OAEs with neurophysiological, behavioural, and perceptual assessments may enhance phenotyping and support the development of more individualized diagnostic and treatment approaches.

5.6 Research Question 5: Is there a difference in DPOAE amplitudes between tinnitus and non-tinnitus individuals with a history of recreational noise exposure?

Recreational noise exposure (RNE) has increasingly been recognized as a significant contributor to early subclinical cochlear damage, particularly in populations that present with tinnitus despite ‘normal’ audiometric thresholds. The present study examined whether a self-reported history of RNE modulates HF-DPOAE amplitudes in individuals with tinnitus. The findings revealed that participants with a self-reported history of RNE exhibited significantly reduced DPOAE amplitudes at high frequencies (specifically 8046 Hz and 10078 Hz) compared to those without such exposure, despite having ‘normal’ pure-tone thresholds up to 8 kHz. These results support the hypothesis that RNE serves as a moderating factor in cochlear function and may accelerate OHC dysfunction in high-frequency regions of the cochlea.

This aligns with prior studies showing that DPOAEs, particularly above 8 kHz, are sensitive to early-stage cochlear damage associated with cumulative acoustic trauma

(Marshall et al., 2001; Jedrzejczak et al., 2022). The basal turn of the cochlea, responsible for encoding high-frequency sounds, is particularly vulnerable to oxidative stress and metabolic disruption from chronic noise exposure (Kujawa & Liberman, 2009). Recreational sources of such exposure, including activities such as attendance at concerts, use of personal listening devices, and clubbing, has been linked to reduced OAE amplitudes even in the absence of audiometric threshold elevation (Le Prell et al., 2013; Liberman et al., 2016). Ueberfuhr et al. (2020) further reported that individuals with tinnitus and 'normal' audiograms exhibited significant DPOAE reductions at high frequencies, with noise history acting as a key stratifying variable.

In the present study, participants with tinnitus and RNE demonstrated steeper HF-DPOAE declines, suggesting a dose-response relationship between cumulative RNE and subclinical cochlear impairment. This is consistent with findings by Job et al. (2007), who identified DPOAE amplitude reductions at 2-6 kHz in noise-exposed individuals, and more recent work by Ami et al. (2024), which reported that RNE was associated with significantly attenuated DPOAEs at 6-12 kHz in young adults with tinnitus.

Importantly, these findings support the concept of RNE as a moderating factor in cochlear function. While tinnitus can occur in individuals without significant noise exposure, those with higher cumulative exposure may be more susceptible to OHC damage in frequency regions beyond the range of standard audiometry. This suggests that RNE may not only contribute to the initiation of tinnitus but may also exacerbate underlying cochlear vulnerability, thereby influencing the degree of peripheral involvement in tinnitus pathology. Moreover, individuals with RNE may present with a tinnitus subtype more directly linked to peripheral dysfunction, as opposed to centrally driven mechanisms seen in other populations (Henry et al., 2014; De Ridder et al., 2015).

The clinical implications of these findings are notable. First, they underscore the need to incorporate detailed noise exposure histories into tinnitus assessments protocols, particularly when evaluating patients with 'normal' audiometric profiles. Second, they support the routine use of HF-DPOAE testing as a means of detecting early cochlear changes that might otherwise go unnoticed. DPOAE reductions in frequencies above 8 kHz may be one of the earliest indicators of subclinical cochlear dysfunction in at-risk populations. Third, these findings highlight the value of preventive strategies and targeted hearing health education, especially for young adults regularly exposed to high sound levels. Public health messaging, the promotion of safe listening habits, and early screening in noise-exposed individuals may help mitigate long-term cochlear damage and tinnitus risk.

Nevertheless, some caution is warranted. Noise exposure was assessed through self-report, which is subject to recall bias and lacks the accuracy of more objective measurement methods, such as sound level monitoring or exposure tracking. Additionally, individual susceptibility to noise-induced damage varies widely due to genetic and lifestyle factors (Sliwinska-Kowalska & Davis, 2012). Despite these limitations, the consistent pattern of reduced DPOAE amplitudes in noise-exposed tinnitus participants in this study reinforces the role of RNE as a clinically relevant modifier of cochlear health.

A total of 24 comparisons were conducted across 12 frequencies for both ears. To mitigate the risk of Type I errors associated with multiple comparisons, a Bonferroni correction was applied. Although several uncorrected *p*-values fell below the .05 threshold, most notably at 1270 Hz in the right ear ($p = .029$), none retained statistical significance after correction. These findings suggest a potential trend toward reduced DPOAE amplitudes in noise-exposed individuals, particularly at higher frequencies however, these differences did

not achieve statistical significance within the current sample. This outcome may reflect subtle cochlear effects, sample size limitations, or inter-individual variability in cochlear function.

Despite the lack of statistically significant results, the observed patterns are consistent with the hypothesis of early cochlear alterations in noise-exposed individuals and highlight the need for further research using larger, more powered samples. Incorporating noise history and high-frequency emissions testing into clinical protocols may improve early identification of cochlear damage and inform more personalized approaches to tinnitus management and prevention.

5.7 Research Question 6: What role do age-related changes play in the interpretation of DPOAE profiles in adults with tinnitus?

Age is a well-documented factor influencing OAE amplitudes, particularly at high frequencies, where age-related OHC vulnerability to cumulative damage begins to manifest (Malviya & Saravanan, 2024). In the context of tinnitus research, age must therefore be carefully considered when interpreting DPOAE data, as subtle declines in cochlear function may reflect either ‘normal’ aging processes, pathology associated with tinnitus, or an interaction between both.

In the present study, the age range of participants was relatively constrained which helped limit the potential confounding effect of aging on group comparisons. However, even within this narrow range, subtle age-related changes may have contributed to the observed variation in DPOAE amplitudes, particularly at high frequencies. A slight but consistent downward trend in amplitudes among older participants, although not statistically significant, suggests that age may act as a cumulative stressor on cochlear function, potentially interacting with other tinnitus-related factors such as RNE or genetic predisposition (Le Prell et al., 2013; Sliwinska-Kowalska & Davis, 2012).

These findings are consistent with previous literature showing that DPOAE amplitudes begin to decline naturally with age, as early as the third decade of life, particularly at frequencies above 6 kHz (Abdala & Dhar, 2012; Prendergast et al., 2019; Malviya & Saravanan, 2024). This age-related cochlear degeneration is commonly attributed to progressive OHC loss, cumulative oxidative stress, and mitochondrial dysfunction- especially in the basal region of the cochlea, where high-frequency sounds are processed (Schmiedt, 2010). Even in the absence of threshold shifts on PTA, these microstructural changes can result in attenuated DPOAE responses, making it difficult to disentangle normative age-related decline from tinnitus-specific cochlear pathology.

In this study, one-way ANOVA analyses comparing DPOAE amplitudes across age bands revealed no statistically significant differences. However, graphical trends indicated a modest amplitude peak in the 25-30 age group and a downward shift among participants aged 36-40. These findings are consistent with those of Jedrzejczak et al. (2023), who reported increasing inter-individual variability in high-frequency DPOAEs with advancing age, even among audiometrically ‘normal’ adults. This variation in decreased OHC responsiveness highlights the challenge of attributing emission reductions solely to tinnitus, as age may act as a low-grade confounder.

While statistical power to detect subtle age effects was limited due to sample size and age homogeneity, the pattern of results supports the notion that age-related cochlear changes, though mild, should not be overlooked when interpreting DPOAE data. As Fabijańska et al. (2012) emphasized, even modest age differences between tinnitus and control groups can confound OAE comparisons if not properly accounted for. In light of this, future studies should either match groups by age or include it as a covariate in statistical modelling.

Moreover, the interaction between age and other factors such as RNE, genetic predisposition, and lifestyle should be considered. Some individuals may demonstrate resilient OHC function into their late 30s, while others experience earlier decline, potentially influenced by cumulative environmental stressors (Le Prell et al., 2013; Sliwinska-Kowalska & Davis, 2012). This individual variability complicates efforts to understand age-related cochlear changes from tinnitus-specific dysfunction.

5.8 Conclusion

This chapter explored the diagnostic value of HF-DPOAEs in individuals with tinnitus who present with 'normal' audiometric thresholds. The findings revealed subtle but consistent reductions in emission amplitudes among tinnitus participants, particularly at higher frequencies, reinforcing the notion of subclinical cochlear dysfunction which often goes undetected by conventional audiometry. These patterns, along with exploratory insights into tinnitus characteristics and moderating factors such as noise exposure and age, support the relevance of DPOAEs as part of a more sensitive and comprehensive test battery for tinnitus assessment.

While some results were limited by statistical power or variability, the overall trends align with theoretical models of OHC degradation and the Discordant Damage Theory, offering a meaningful contribution to ongoing efforts in refining tinnitus diagnostics. Importantly, these findings underscore the need for multimodal, individualized approaches in clinical practice.

The next and final chapter will synthesize the overall outcomes of this study, reflect on its implications for clinical audiology and tinnitus research, and propose directions for future investigation.

Chapter 6: Conclusion

This chapter presents a comprehensive conclusion to the study by summarizing the key findings, acknowledging methodological limitations, and outlining directions for future research. It also highlights the clinical implications of the results and offers final reflections on the contribution of high-frequency distortion product otoacoustic emissions (HF-DPOAEs) to tinnitus assessment in individuals with clinically 'normal' hearing.

6.1 Summary of Key Findings

- Subclinical cochlear attenuation in the tinnitus group: Statistically significant reductions in DPOAE amplitudes were identified at frequencies ≥6154 Hz in the tinnitus group, supporting the hypothesis of subtle outer hair cell (OHC) dysfunction not detectable by standard audiometry.
- Frequency-specific cochlear changes: No major group differences were observed at low to mid frequencies, but a consistent amplitude decline was evident in the high-frequency range among tinnitus participants, suggesting apical cochlear involvement.
- No strong correlations with tinnitus severity: Although weak trends were observed, there was no statistically significant correlation between DPOAE amplitude and tinnitus impact scores. This suggests that while peripheral dysfunction may contribute to tinnitus perception, the severity is likely shaped by central mechanisms, aligning with the neurophysiological model.
- Minimal interaural asymmetries: Unilateral tinnitus participants did not exhibit significant amplitude differences between tinnitus and non-tinnitus ears, aligning with prior findings that tinnitus lateralization does not always reflect cochlear asymmetry.

- Noise Exposure Impact: Tinnitus participants with self-reported recreational noise exposure showed further reductions in HF-DPOAEs, reinforcing the importance of obtaining a history of noise exposure in assessing cochlear vulnerability.

6.2 Limitations and Suggestions for Improvement

Several limitations should be acknowledged:

1. **S**ample Size and Composition: The relatively small sample size, especially within subgroups, and the gender imbalance observed in the control group may have reduced the statistical power of the analyses and limited the generalisability of the findings to the wider tinnitus population.
2. Classification of 'normal' hearing thresholds: While all participants met the clinical criteria for 'normal 'auditory thresholds (≤20 dB HL from 250 Hz to 8 kHz), the study did not account for potential subclinical declines in hearing sensitivity. For instance, a participant who previously had thresholds around 5 dB HL across all frequencies but now measures at 20 dB HL would still fall within the 'normal' range yet may have experienced a meaningful deterioration in cochlear function. Without baseline audiometric data, it is difficult to determine whether observed differences in DPOAEs reflect true cochlear abnormalities or undetected shifts within the clinically 'normal' range.
3. Cross-sectional Design: The cross-sectional nature of the study limits the ability to observe temporal changes in DPOAE amplitudes or tinnitus perception. As a result, it was not possible to assess the progression of cochlear function or symptom variability over time. A longitudinal approach may be able to explore the progression which may be important for understanding the dynamic nature of tinnitus.

4. HF-DPOAE Reliability: Additionally, technical constraints in the ultra-high-frequency range, particularly at the high frequency range, may have contributed to variability in DPOAE measurements. Factors such as reduced signal-to-noise ratios, probe placement inconsistencies, and equipment sensitivity at these frequencies may have impacted data reliability and should be addressed in future studies through enhanced calibration protocols or alternative recording methods.
5. The influence of uncontrolled confounding variables: Stress levels, sleep quality, and undiagnosed auditory or neurological conditions may have affected participants' self-reported tinnitus experiences. These factors are known to modulate tinnitus perception and could have introduced additional variability into the findings, underscoring the need for more comprehensive participant profiling in future research.
6. Use of supra-aural headphones: A limitation of the study is the use of supra-aural earphones during pure-tone audiometry (PTA). While common in clinical settings, they are more prone to positioning errors and ear canal occlusion, potentially introducing variability in threshold measurements. Insert earphones would have provided more accurate and consistent results by minimizing such issues.
7. Pitch Matching and Frequency Alignment: Tinnitus pitch was not individually matched to DPOAE frequency bands. Future studies could adopt frequency-specific matching protocols to better link perceived tinnitus with cochlear emission profiles.

Despite these limitations, rigorous procedures were implemented throughout the study to ensure the accuracy, consistency, and reliability of the collected data. While certain methodological constraints may have influenced the outcomes, the findings nonetheless provide valuable insights into the role of HF- DPOAEs in tinnitus assessment. Addressing these limitations in future research will further enhance the validity and clinical applicability of this line of investigation.

6.3 Recommendations for Future Research

To further advance the field and build upon the findings of this study, future research should consider the following directions:

1. Employ larger, gender-balanced, and stratified samples

   Future studies should aim to recruit larger, more demographically balanced samples, particularly with regard to gender distribution and subgroup representation (e.g., unilateral tinnitus). This would enhance statistical power and improve the generalisability of findings.
2. Develop normative datasets for DPOAEs across a wide range of frequencies and diverse age groups.

   Establishing age-specific normative values across frequencies, particularly past 8 kHz, would improve the interpretability of DPOAE amplitudes and allow for more precise identification of subclinical cochlear dysfunction.
3. Baseline Hearing Data and Hearing History.

   Including retrospective or longitudinal audiometric data would help differentiate between lifelong ‘normal’ hearing and subtle, undetected declines. This would clarify whether observed changes in DPOAEs reflect ongoing deterioration or stable hearing within clinical norms.
4. Adopt Longitudinal Designs to Explore Prognosis and Treatment Responsiveness

   Longitudinal studies would allow researchers to monitor changes in DPOAE amplitudes and tinnitus perception over time, offering insights into the progression of cochlear dysfunction. This approach could also help determine whether specific DPOAE patterns are predictive of symptom persistence, improvement, or

responsiveness to clinical interventions, thereby enhancing their potential use in prognosis and personalised treatment planning.

5. Extended High-Frequency and Frequency-Matched Testing

   Further research should include even higher frequency DPOAE testing (above 12 kHz) where possible, along with individualised tinnitus pitch matching. This would allow for a more precise analysis of whether specific DPOAE frequency bands align with participants' tinnitus characteristics.

6. Multimodal Diagnostic Approaches.

   Combining DPOAEs with additional objective measures—such as auditory brainstem responses (ABRs), cortical evoked potentials, or functional imaging—could provide a more comprehensive understanding of tinnitus pathophysiology and improve diagnostic precision.

6.4 Clinical Implications

From a clinical standpoint, the study underscores the utility of HF-DPOAEs as a valuable addition to the tinnitus diagnostic battery. Their ability to detect early or subtle cochlear dysfunction provides a non-invasive, objective tool to complement self-reported symptomatology, especially in individuals whose conventional audiograms appear within ‘normal’ thresholds. Such insight may improve diagnostic accuracy, reduce misdiagnosis, and support earlier intervention in at-risk populations such as those with a history of noise exposure or young adults with early-onset tinnitus.

One of the most impactful clinical contributions of this study lies in validating the symptoms of individuals with tinnitus who present within ‘normal’ audiometric thresholds. Traditionally, the absence of measurable hearing loss on PTAs has often led to underdiagnoses, minimisation, or even dismissal of patient-reported tinnitus. This study

challenges that limitation by demonstrating that subclinical cochlear dysfunction, as evidenced by reduced HF-DPOAE amplitudes, can exist despite 'normal' hearing thresholds.

By identifying objective physiological changes in OHC function, particularly at frequencies beyond 8000 Hz, this research provides a biological explanation for tinnitus perception in these individuals. Clinicians can use this information to reassure patients that their symptoms are not illusory or exaggerated but are underpinned by subtle, measurable alterations in cochlear function. This validation is essential for improving patient trust, compliance, and engagement with tinnitus management strategies.

Moreover, these findings have important implications for hearing conservation, particularly in younger adults or individuals with occupational and recreational noise exposure. The study revealed that participants with a history of RNE exhibited greater reductions in HF-DPOAEs, suggesting that cochlear damage may begin long before it becomes evident in standard audiometry. This supports the notion that tinnitus can be an early warning sign of cochlear stress, and highlights the need for preventive education and proactive hearing protection.

Clinicians should take the opportunity to educate individuals with tinnitus as well as the general public, especially those who may not recognize the risk, about the importance of avoiding harmful noise exposure and using ear protection in high-risk environments. This approach reframes tinnitus not only as a manageable condition but also as a valuable indicator for broader auditory health monitoring.

Incorporating HF- DPOAE testing into routine clinical evaluations of tinnitus patients may therefore serve a dual purpose: providing physiological validation of tinnitus complaints and functioning as a preventive tool in hearing health promotion. This dual role underscores

the importance of expanding clinical protocols beyond standard audiometry to better support early diagnosis, patient reassurance, and long-term auditory well-being.

The implementation of HF- DPOAEs in routine clinical practice could aid in distinguishing between tinnitus subtypes and identifying those with underlying cochlear pathology. This, in turn, may inform tailored treatment strategies, including auditory training, counselling, and preventative measures targeting cochlear preservation.

6.5 Final Remarks

In summary, the findings of this study support the clinical utility of ultra-high-frequency DPOAEs as a sensitive and non-invasive tool for detecting cochlear dysfunction in tinnitus patients with clinically 'normal' audiograms. Although not universally predictive, DPOAEs provide valuable markers of subclinical cochlear changes and may enhance tinnitus diagnostics when used alongside subjective symptom reports and conventional audiometry. Their ability to detect subtle outer hair cell deficits at high frequencies positions them as a valuable adjunct to traditional assessments, with potential applications in early diagnosis, prevention, and personalised tinnitus management.

Further research is needed to refine measurement protocols, develop normative datasets, and examine longitudinal changes in high-frequency emissions across various tinnitus subtypes. Ultimately, this study adds to the growing body of evidence advocating for the inclusion of frequency-specific, objective testing in tinnitus assessment and highlights the importance of transitioning towards a more preventative and patient-centred model of hearing healthcare.

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Appendices

Appendix A: Information Sheet English

L-Università ta' Malta

Participants` Information Sheet

Dear Participant,

My name is Laura Mercieca, and I am currently reading for a Master of Science in Audiology at the University of Malta. As part of my course requirements, I am conducting a research study entitled, 'Otoacoustic Emissions as a part of the Test Battery for Tinnitus Diagnosis' (FHS-2024-00221). The aim of this study is to investigate the differences in Otoacoustic Emissions (OAEs) in individuals with tinnitus and those without to determine whether OAEs serve as a predictive clinical tool in tinnitus management. Your participation in this study would help us gain a better understanding about the possible links between tinnitus and cochlear function in adults. Furthermore, all data collected from this research shall be used solely for the purpose of this study.

You are being invited to participate in a study which will investigate whether OAEs reveal additional insight into the functioning of the inner ear in adults with tinnitus. If you agree to participate, you will meet the researcher once, at 'Loud and Clear- Professional Audiology Services' a private audiology clinic in Gzira at a time most suitable for you as much as possible, for approximately for approximately 45 minutes.

During the visit I, as the researcher will:

1. Ask some general questions about you, such as your age and medical history.
2. You will be asked to fill in a short, scaled questionnaire on tinnitus perception.
3. You will undergo a set of audiological assessments under the supervision of a qualified audiologist.

Data obtained from the questionnaire, interview and audiological assessments, specifically Distortion Product Otoacoustic Emissions, will be recorded on a data sheet on the researcher's personal computer that is password protected and in an encrypted format.

There are no risks involved in participating in this study.

You are not obliged to participate in this study or to answer all the questions and you may withdraw from the study at any time without giving a reason. Furthermore, withdrawal from the study will not have any negative repercussions on you. Should you choose to withdraw, any data collected will be erased as long as this is technically possible (for example, before it is anonymised or published), unless erasure of data would render impossible or seriously impair achievement of the research objectives, in which case it shall be retained in an anonymised form. I can assure

Thank you for your time and consideration. Should you have any questions or concerns do not hesitate to contact me on [redacted] or my supervisor Dr Nadine Tabone on [redacted]

Yours Sincerely,

[redacted]

Laura Mercieca

[redacted]

Researcher

[redacted]

Dr Nadine Tabone

[redacted]

Research Supervisor

Appendix B: Information Sheet in Maltese

L-Università ta' Malta

Formola ta' Tagħrif għall-Parteċipanti

Għażiż/a Parteċipant/a,

Jiena Laura Mercieca, fil-preżent qed insegwi Masters fl- Awdjoloġija fl- Universita' ta Malta . Bħala parti mir-rekwiżiti tal-kors, qed nagħmel riċerka bit-titlu, 'Otoacosutic Emissions as a part of the Test Battery for Tinnitus Diagnosis' (FHS-2024-00221). L-għan ta 'dan l-istudju huwa li jinvestiga d-differenzi fl-Emissjonijiet Otoakustiċi (OAEs) f'individwi b'tinnitus u dawk mingħajr biex jiddetermina jekk OAEs iservux bħala għodda klinika ta' tbassir fil-ġestjoni tat-tinnitus. Il-parteċipazzjoni tiegħek f'dan l-istudju tgħinna niksbu fehim aħjar dwar ir-rabtiet possibbli bejn it-tinnitus u l-funzjoni tas-smigħ fl-adulti. Kull informazzjoni miġbura tintuża biss għall-għan jew l-għanijiet ta' dan l-istudju.

Jekk taċċetta li tieħu sehem, inti tintalab sabiex tiltaqa' mar-riċerkatriċi Laura Mercieca darba f' f'Loud and Clear- Professional Audiology Services' klinika privata tal- Awdjoloġija fil- Gżira f'ħin li jkun konvenjenti għalik. Din il-laqgħa se tieħu madwar 45 minuta.

Waqt din il-laqgħa jiena nkun nista':

1. Nistaqsi xi mistoqsijiet dwarek, pereżempju l-età' tiegħek, u xi mistoqsijiet dwar is-saħħa tiegħek.
2. Int ħa timla kwestjonarju qasir u skalat dwar il-perċeszzjoni tat- tinnitus.
3. Jitwettaq sett ta' valutazzjonijiet awdoloġiċi taht is- supervizjoni ta' professjonist kwalifikat.

Id- dejta se tigi irrekordjata bil-miktub, din tinkludi r-riżultati mill-valutazzjonijiet awdjoloġiċi, speċifikament id- 'Distrotion Product Otoacosutic Emissions' kif ukoll l-informazzjoni pprovduta fil-kwestjonarju u l-intervista. Id-data kollha se jinħażnu fuq il-kompjuter personali tar-Riċerkatriċi permezz ta' kodifikazzjoni tad-data (data encryption) u li hi protetta b'password.

M'hemm l-ebda riskju involut fil-parteċipazzjoni f'dan l-istudju.

M'intix obbligat/a li twieġeb il-mistoqsijiet kollha u tista' twaqqaf l-istudju fi xħin trid mingħajr ma tagħti l-ebda raġuni. Dan mhux ħa jkollu riperkussjonijiet negattivi fuqek. Jekk tagħżel li tirtira mir-riċerka, l-informazzjoni li tkun laħqet ittieħdet fl-intervista miegħek titħassar dment li dan ikun teknikament possibbli (ngħidu aħna, qabel ma tiġi anonimizzata jew ippubblikata), u sakemm l-għanijiet tar-riċerka jkunu jistgħu jintlaħqu u ma jintlaqtux serjament. F'dak il-każ, l-informazzjoni tiegħek tintuża u tinżamm anonima.

Nassigurak li se tinżamm il-kunfidenzjalità matul l-istudju kollu u l-identità tiegħek u kull informazzjoni personali miġbura mhuma se jiġu żvelati mkien fit-teżi, ir-rapporti, il-preżentazzjonijiet u/jew il-pubblikazzjonijiet li jistgħu jirriżultaw minnha. Kull tagħrif miġbur se jiġi psewdonomizzat, jiġifieri id-data kollha se tkun protetta permezz ta' sistema ta' kodiċi u miżmuma separatament mill-informazzjoni personali.

Ir-Riċerkatriċi biss ser ikollha aċċess għall-informazzjoni miġbura, filwaqt li s-Superviżura akkademika u l-eżaminaturi se jkollhom biss aċċess għal data kkodifikata. Is-Superviżuri akkademiċi u l-eżaminaturi jista jkollhom bżonn aċċess għall-informazzjoni miġbura għal skop ta' verifika. Id-data kollha se jinħażnu offline f'verżjoni kriptata fuq hard drive estern. Barra minn hekk, il-materjal stampat se jinqafel f'post sigur.

F'każ li tħoss li l-istudju ħoloqlok diffikultà u tixtieq li tiddiskuti x'qed tħoss ma' professjonist/a mill-qasam tal-kura tas-saħħa, Dr Nadine Tabone [Awdjoloġista li tista tiġi ikkuntatjata fuq 23401143] se tkun qed tipprovdi servizz ta' għajnuna mingħajr ħlas min-naħa tiegħek.

Il-parteċipazzjoni tiegħek f'dan l-istudju hija għażla għal kollox volontarja u inti ħieles/ħielsa li taċċetta jew tirrifjuta li tieħu sehem mingħajr ma jkun hemm konsegwenzi fil-konfront tiegħek. Se tingħata kopja tal-ittra ta' informazzjoni u tal-formula ta' kunsens sabiex tkun tista' taċċessahom fil-futur. Barra minn hekk, skont ir-Regolamenti Ġenerali dwar il-Protezzjoni tad-Data (GDPR) u l-leġiżlazzjoni nazzjonali li timplimenta u tispeċifika aktar il-provvedimenti relevanti tar-regolamenti msemmija, inti għandek id-dritt li taċċessa, tirretifika, u fejn japplika titlob sabiex titħassar id-data li tikkonċerna lilek. L-informazzjoni personali kollha se titħassar meta ma tibqax iktar neċessarja li tinżamm f'Settembru 2025. Id-data li tista' tinħażen b'mod anonimu tista' tinżamm b'mod indefinittiv.

Dan l-istudju ġie approvat mill-Kumitat għall-Etika fir-Riċerka fi ħdan il-Fakultà tax-Xjenzi tas-Saħħa fl-Università ta' Malta.

Huwa importanti li tissemma l-possibbiltà ta' sejbiet inċidentali matul dan l-istudju. Sejbiet inċidentali huma riżultati li huma lil hinn mill-għanijiet tal-istudju iżda jistgħu jkunu sinifikanti għal saħħtek. Jekk xi sejbiet bħal dawn jiġu identifikati, inti tkun infurmat dwarhom. Ir- Riċerkatriċi se jikkomunikaw dawn is-sejbiet, u inti tiġi riferut lill-professjonist tal-kura tas-saħħa xieraq għal aktar intervent u ġestjoni.

Grazzi ħafna tal-ħin u s-sehem tiegħek f'dan l-istudju. F'każ li jkollok xi mistoqsijiet jew tixtieq tiċċara xi ħaġa, tista' ċċempilli fuq [redacted] jew tibgħatli email fuq [redacted] Tista' wkoll tikkuntattja lis-Superviżura Dr Nadine Tabone fuq [redacted] jew billi tibgħat email fuq [redacted]

Dejjem tiegħek,

[redacted]

Laura Mercieca

[redacted]

[redacted]

Dr Nadine Tabone

[redacted]

Appendix C: Consent Form in English

L-Università ta' Malta

Participants` Consent Form

FHS-2024-00221

I, the undersigned, give my consent to take part in the study conducted by Laura Mercieca. The purpose of this document is to specify the terms of my participation in this research study.

1. I have been given written and verbal information about the purpose of the study and all questions have been answered.
2. I understand that I have been invited to participate in a study, in which the researcher will ask questions and perform tests to investigate whether OAEs reveal additional insight into cochlear function in adults with tinnitus.
3. I am aware that the meeting will take approximately 45 minutes. I understand that the meeting is to be conducted at 'Loud and Clear- Professional Audiological Services' at a time most suitable for me as much as possible.
4. I am aware that measurements produced by the audiological assessments, as well as my responses to the questionnaire and interview, will be recorded on a data sheet on the researcher's personal computer that is password protected and in an encrypted format.
5. I am aware that the data collected will be coded and that this data will be stored securely and separately from any codes and personal data.
6. I am aware that the researcher is the only person who has access to this data. The academic supervisor/s and examiners will typically have access to coded data only. There may be exceptional circumstances which allow the supervisor and examiners to have access to personal data too, for verification purposes.
7. I am also aware that the coded data files shall be stored offline in an encrypted version on an external hard drive. Any material in hard-copy form will be placed in a locked cupboard and kept until results are published.
8. I am aware that my identity and personal information will not be revealed in any publications, reports or presentations arising from this research.
9. I also understand that I am free to accept, refuse or stop participation at any time without giving any reason. This will have no negative repercussions on myself and that any data collected form me will be erased. Data will be stored anonymously if it is impossible to delete.
10. I also understand that my contribution will serve to explore the link between tinnitus and auditory functioning in adults.

11. I understand that under the General Data Protection Regulation (GDPR) and national legislation that implements and further specifies the relevant provisions of said regulation, I have the right to access, rectify, and where applicable ask for the data concerning me to be erased.
12. I also understand that personally identifiable data will be deleted when it is no longer necessary, which should be in September 2025. Any subsequent anonymised data may be kept indefinitely.
13. I will be provided with a copy of the information letter and consent form for future reference.
14. I have read and understood the points and statements of this form. I have had all the questions answered to my satisfaction, and I agree to participate in this study.

Participant: _____

Signature: _____

Date: _____

[redacted] [redacted]

Laura Mercieca **Dr Nadine Tabone**

Researcher Research Supervisor

[redacted] [redacted]

Appendix D: Consent Form in Maltese

L-Università ta' Malta

Formola ta' Kunsens tal-Parteċipanti

FHS-2024-00221

Jien, hawn taħt iffirmat/a, nagħti l-kunsens tiegħi biex nieħu sehem fl-istudju mmexxi minn Laura Mercieca. L-għan ta' dan id-dokument hu li jiġu speċifikati t-termini tal-parteċipazjoni tiegħi f'dan l-istudju ta' riċerka.

1. Jien ingħatajt informazzjoni miktuba u verbali dwar l-għan tal-istudju u l-mistoqsijiet kollha twieġbu.
2. Nifhem li se nkun qed nipparteċipa fi studju, fejn ir- Riċerkatriċi ħa tinvestiga jekk OAEs jiżvelawx għarfien addizzjonali dwar il-funzjoni tal-kokleari f'adulti b'tinnitus.
3. Naf li l-istudju se jieħu madwar 45 minuta. Nifhem, li l-laqgħa se ssir 'Loud and Clear- Professional Audiological Services' f'ħin konvenjenti għalija.
4. Jien konxju/a li r-riżultati tiegħi se jkunu qed jiġu rrekordjati u se jinkitbu r-risposti fuq formuli apposta. Kif ukoll it-tweġibiet tiegħi għall-kwestjonarju u l-intervista, se jiġu rreġistrati. Id-data kollha se jinħażnu fuq il-kompjuter personali tar-Riċerkatriċi permezz ta' kodifikazzjoni tad-data (data encryption) u li hi protetta b'password.
5. Naf ukoll li se ssir kodifikazzjoni tad-data u din se tinżamm separatament mill-informazzjoni personali.
6. Naf ukoll li r-Riċerkatriċi hi l-unika persuna li se jkollha aċċess għal din l-informazzjoni, filwaqt li s-Superviżura akkademika u l-eżaminaturi se jkollhom aċċess għal data kkodifikata biss. Is-Superviżura akkademika u l-eżaminaturi jista jkollhom bżonn aċċess għall-informazzjoni miġbura għal skop ta' verifika.
7. Barra min hekk, d-data se jinħażnu offline f'verżjoni kriptata fuq hard drive estern. Barra minn hekk, naf li l-materjal stampat se jitqiegħed f'post sikur u se jinżamm sakemm joħorġu r-riżultati.
8. Naf li l-identità tiegħi u l-informazzjoni personali mhuma se jinkixfu mkien fit-teżi, fir-rapporti, fil-preżentazzjonijiet u/jew fil-pubblikazzjonijiet li jistgħu jirriżultaw minnha.
9. Nifhem ukoll li jien liberu/a li naċċetta, nirrifjuta jew inwaqqaf il-parteċipazzjoni f'kull ħin bla ma nagħti raġuni. Dan mhux ħa jkollu riperkussjonijiet negattivi fuqi. Nifhem ukoll li la darba nirtira minn dan l-istudju, l-informazzjoni miġbura se titħassar.
10. Nifhem ukoll li l-kontribuzzjoni tiegħi ser isservi biex tesplora r-rabta bejn it-tinnitus u l-disfunzjoni taċ-ċelluli tax-xagħar ta' barra fl-adulti.
11. Naf li l-informazzjoni personali kollha se titħassar meta ma tibqax iktar neċessarja li tinżamm f'Settembru 2025. Id-data li tista' tinħażen b'mod anonimu tista' tinżamm b'mod indefinittiv.

12. Nifhem ukoll, li skont ir-Regolamenti Ġenerali dwar il-Protezzjoni tad-Data (GDPR) u l-leġiżlazzjoni nazzjonali li timplimenta u tispeċifika aktar il-provvedimenti relevanti tar-regolamenti msemmija, jiena għandi d-dritt li naċċessa, nirretifika, u fejn japplika nitlob sabiex titħassar id-data li tikkonċernani.
13. Fl-aħħar nett, naf ukoll li se ningħata kopja tal-ittra ta' informazzjoni u tal-formola ta' kunsens sabiex inkun nista' naċċessahom fil-futur.
14. Jien qrajt u fhimt il-punti u d-dikjarazzjonijiet f'din il-formula. Inħossni sodisfatt/a bit-tweġibiet li ngħatajt għall-mistoqsijiet li kelli, u qed naċċetta minn jeddi li nipparteċipa f'dan l-istudju.

Parteċipant:_____

Firma:_____

Data:_____

Isem is-Superviżur/a tar-riċerka:

[redacted]

Firma:_____

Laura Mercieca

[redacted]

Isem ir-Riċerkatur / Riċerkatriċi:

[redacted]

Firma: _____

Dr Nadine Tabone

[redacted]

Appendix E: Participant Recruitment Poster

CALL FOR PARTICIPANTS

Otoacoustic Emissions as a part of the Test Battery for Tinnitus Diagnosis

We are looking for:

- 18- 40 year-olds
- Experience tinnitus (ringing or buzzing in the ears)
- Have normal hearing

For further information, access the following link:
English: https://rb.gy/wo1098
Maltese: https://rb.gy/uut7pp

Should you have any questions or wish to participate, please contact Laura Mercieca on [redacted]

Appendix F: Letters Requesting Permissions

L-Università ta' Malta

Dear [redacted]

My name is Laura Mercieca and I am a student at the University of Malta, presently reading for a Master's of Science in Audiology. I am presently conducting a research study for my dissertation titled 'Otoacoustic Emissions as a part of the Test Battery for Tinnitus Diagnosis', this is being supervised by Dr Nadine Tabone.

The aim of my study is to explore differences in DPOAEs in individuals, aged between 18-40 years, with normal hearing thresholds and tinnitus, as well as normal hearing thresholds without tinnitus. The aims of the study are to determine the incidence outer hair cell dysfunction in individuals with tinnitus and normal hearing thresholds, as well as exploring the diagnostic and prognostic value of OAE measurements in the clinical assessment of tinnitus. The assessment process will consist of administering a brief case history as well as a scaled tinnitus questionnaire, followed by a series of audiological tests including otoscopy, tympanometry, pure-tone audiometry, and distortion- product otoacosutic emissions.

All data collected will be stored in a pseudonymised form and erased on completion of the study and publication of results. All hard copies of data collection will be securely stored in a locked cabinet, and all soft copies shall be stored in an encrypted disk and USB, only the researcher, research supervisor, and examiners will have access to these.

I am therefore requesting your assistance in acting as an intermediary between participants, with the aim that initial contact will be anonymous to myself, the researcher. I am also requesting your permission for the assessment process to be carried out at 'Loud and Clear- Professional Audiology Services', using the necessary equipment. The subjects will be

identified from the clinic's database, according to the selection criteria supplied. Participants must fit into the following selection criteria:

- Adults aged 18-40 years
    - Group 1: Subjective, chronic tinnitus, and pure-tone audiometric thresholds within the normal range (≤ 25 dB HL) up to 8000Hz.
    - Group 2: No self-reported tinnitus and pure- tone audiometric thresholds within the normal range (≤ 25 dB HL) up to 8000Hz.
- Exclusion Criteria: On-going otologic diseases, acoustic trauma, vestibular problems, ototoxic drug intake, or psychotropic medication.

Following this, they will be contacted and invited to participate in the study by yourself, the intermediary. Should they consent to participation, then they can contact me on the details provided in the recruitment letter.

The assessment will be carried out by the researcher and supervised by a qualified audiologist.

Yours Sincerely,

Laura Mercieca

Researcher

Dr Nadine Tabone

Research Supervisor

Dear [redacted]

My name is Laura Mercieca and I am a student at the University of Malta, presently reading for a Master's of Science in Audiology. I am presently conducting a research study for my dissertation titled 'Otoacoustic Emissions as a part of the Test Battery for Tinnitus Diagnosis; this is being supervised by Dr Nadine Tabone.

The aim of my study is to explore differences in DPOAEs in individuals, aged between 18-40 years, with normal hearing thresholds and tinnitus, as well as normal hearing thresholds without tinnitus. The aims of the study are to determine the incidence outer hair cell dysfunction in individuals with tinnitus and normal hearing thresholds, as well as exploring the diagnostic and prognostic value of OAE measurements in the clinical assessment of tinnitus. The assessment process will consist of administering a brief case history as well as a scaled tinnitus questionnaire, followed by a series of audiological tests including otoscopy, tympanometry, pure-tone audiometry, and distortion- product otoacosutic emissions.

. Participants must fit into the following selection criteria:

- Adults aged 18-40 years
    - Group 1: Subjective, chronic tinnitus, and pure-tone audiometric thresholds within the normal range (≤ 25 dB HL) up to 8000Hz.
    - Group 2: No self-reported tinnitus and pure- tone audiometric thresholds within the normal range (≤ 25 dB HL) up to 8000Hz.
- Exclusion Criteria: On-going otologic diseases, acoustic trauma, vestibular problems, ototoxic drug intake, or psychotropic medication.

All data collected will be stored in a pseudonymised form and erased on completion of the study and publication of results. All hard copies of data collection will be securely stored in a locked cabinet, and all soft copies shall be stored in an encrypted disk and USB, only the researcher and supervisor, Dr Nadine Tabone, will have access to these.

I am seeking assistance in acting as an intermediary to facilitate communication between potential research participants, ensuring that initial contact remains anonymous to me as the researcher. The intermediary's role would involve discreetly distributing the request for participation to all students, while maintaining confidentiality regarding my identity.

Yours Sincerely,

[redacted]

Laura Mercieca

[redacted]

Researcher

[redacted]

Dr Nadine Tabone

[redacted]

Research Supervisor

Dear [redacted]

My name is Laura Mercieca and I am a student at the University of Malta, presently reading for a Master's of Science in Audiology. I am presently conducting a research study for my dissertation titled 'Otoacoustic Emissions as a part of the Test Battery for Tinnitus Diagnosis; this is being supervised by Dr Nadine Tabone.

The aim of my study is to explore differences in OAEs in individuals, aged between 18-60 years, with tinnitus and those without in conjunction with a mild hearing loss or no hearing loss, whilst also analysing the correlation subjective tinnitus measures and objective OAE measures. The assessment process will consist of administering a brief case history as well as a scaled tinnitus severity questionnaire, followed by a series of audiological tests including otoscopy, tympanometry, pure-tone audiometry, and distortion- product otoacosutic emissions.

. Participants must fit into the following selection criteria:

- Adults aged 18-60 years
    - Group 1: Subjective, chronic tinnitus, and pure-tone audiometric thresholds within the normal range (≤ 25 dB HL) up to 8000Hz.
    - Group 2: No self-reported tinnitus and pure- tone audiometric thresholds within the normal range (≤ 25 dB HL) up to 8000Hz.
- Exclusion Criteria: On-going otologic diseases, acoustic trauma, vestibular problems, ototoxic drug intake, or psychotropic medication.

All data collected will be stored in a pseudonymised form and erased on completion of the study and publication of results. All hard copies of data collection will be securely stored in a locked cabinet, and all soft copies shall be stored in an encrypted disk and USB, only the researcher and supervisor, Dr Nadine Tabone, will have access to these.

I am seeking assistance in acting as an intermediary to facilitate communication between potential research participants, ensuring that initial contact remains anonymous to me as the researcher. The intermediary's role would involve discreetly distributing the request for participation to all students, while maintaining confidentiality regarding my identity.

Yours Sincerely,

[redacted]

Laura Mercieca

[redacted]

Researcher

[redacted]

Dr Nadine Tabone

[redacted]

Research Supervisor

L-Università ta' Malta

Dear [redacted]

My name is Laura Mercieca and I am a student at the University of Malta, presently reading for a Master's of Science in Audiology. I am presently conducting a research study for my dissertation titled 'Otoacoustic Emissions as a part of the Test Battery for Tinnitus Diagnosis; this is being supervised by Dr Nadine Tabone.

The aim of my study is to explore differences in OAEs in individuals with tinnitus and those without, whilst also analysing the correlation subjective tinnitus measures and objective OAE measures. The assessment process will consist of administering a brief case history as well as a scaled tinnitus questionnaire, followed by a series of audiological tests including otoscopy, tympanometry, pure-tone audiometry, and distortion- product otoacoustic emissions.

I would therefore like to request permission to use the '4C Tinnitus Questionnaire' as part of this series of tests. Given the bilingual context of the population, I would also like request permission to translate the tool to Maltese.

Yours Sincerely,

[redacted]

Laura Mercieca

[redacted]

Researcher

[redacted]

Dr Nadine Tabone

[redacted]

Research Supervisor

Appendix G: Permission for Data Collection

Laura Mercieca

to [redacted]

Dear [redacted]

I trust this email finds you well. I am currently conducting a research study on otoacoustic emission in individuals with normal hearing thresholds and tinnitus. This study is currently being supervised by Dr Nadine Tabone, in copy.

I am reaching out to inquire about the possibility of conducting data collection at your clinic, with you acting as an intermediary. Given your expertise and the diverse patient population you serve, I believe your clinic would provide an ideal setting for gathering valuable data for my study. Your role as an intermediary would involve facilitating participant recruitment and data collection procedures in accordance with ethical guidelines. Your involvement would greatly contribute to the success of this research project.

I have attached further details about the study for your review. I would be grateful for the opportunity to discuss this further at your earliest convenience.

Thank you for considering my request.

Kind regards,

Laura Mercieca.

One attachment • Scanned by Gmail

Permission for Da...

[redacted]

to me

Dear Ms Laura Mercieca,

I would gladly accept be an intermediary for your study.

kind regards

[redacted]

Appendix H: Permission for Dissemination of Social Media Poster

Laura Mercieca

I hope this email finds you well.

I am writing to seek your permission to share my research study on the department's social media page in order to reach potential participants. I am conducting a study on otoacoustic emissions in individuals with normal hearing thresholds and tinnitus, and believe that members of our department would make valuable contributors to this research.

This research study will be supervised by Dr Nadine Tabone, copied to this email. I assure you that the study will adhere to all ethical guidelines prior to data collection, and participant confidentiality will be strictly maintained. Attached you will find detailed information about the study.

Your approval for this request would be greatly appreciated, and I am happy to address any questions or concerns you may have.

Thank you for considering my request.

Kind regards,

Laura Mercieca

One attachment • Scanned by Gmail

Dissemination of ...

Dear Laura

I have not objective to circulating your call for participants on our departmental FB page.

I would advise that you create a poster (which includes the link to the questionnaire and information/consent) so that we can use the poster when advertising your research.

Good luck

Regards

L-Università ta' Malta

Appendix I: Approval from FREC

Draft/Submitted REDP Forms

Show 10 entries Search:

Application ID	Application Date	Project Title	Faculty	Status
FHS-2024-00221	16/07/2024	'Otoacoustic Emissions as a part of the Test Battery for Tinnitus Diagnosis.	Faculty of Health Sciences	Approved

Showing 1 to 1 of 1 entries Previous 1 Next

Appendix J: English Case History Form

Otoacoustic Emissions as Part of the Test Battery for Tinnitus Diagnosis

English- Case History Form

* Indicates required question

Participant Code *: _____

Date of Birth *: _____

Gender *:

- o Male
- o Female
- o Prefer not to say.

Medical history: Brief overview of relevant conditions or past treatments *

_____

Current medications: List of medications being taken *

_____

Do you work in a noisy environment? *

- o Yes
- o No

Have you ever been exposed to loud noises for extended periods? *

- o Yes
- o No

If yes, describe: _____

Do you have any family history of hearing problems or tinnitus? *

- o Yes
- o No

If yes, describe: _____

Onset of tinnitus: Description of when tinnitus was first noticed *

_____

Type of tinnitus: Description of the sound *

- o Ringing
- o Hissing
- o Humming
- o Buzzing
- o Whistling

- o Other: _____

Is the tinnitus constant or intermittent? *

- o Constant
- o Intermittent

Side of tinnitus: Where the tinnitus is predominantly present *

- o Right ear
- o Left ear
- o Both ears
- o Brain

Adapted from Langguth et al. (2007). Tinnitus Sample Case History Questionnaire. Retrieved from tinnitusresearch.net/images/files/migrated/consensusdocuments/en/TINNITUS_SAMPLE_CASE_HISTORY_QUESTIONNAIRE.pdf

Appendix K: Maltese Case History

Otoacoustic Emissions as a part of the Test Battery for Tinnitus Diagnosis
Maltese- Case History Form and Questionnaire
* Jindika mistoqsija meħtieġa

Kodiċi tal-Parteċipant *: _____
Data tat-Twelid *: _____
Storja medika: Ħarsa ġenerali qasira tal-kundizzjonijiet rilevanti jew trattamenti tal-passat *

_____

Mediċini kurrenti: Lista ta' mediċini li qed jittieħdu *

_____

Int taħdem f'ambjent storbjuż? *

- o Iva
- o Le

Qatt ġejt espost għal ħsejjes qawwija għal perjodi estiżi? *

- o Iva
- o Le
- o Jekk iva, spjega:

Għandek xi storja tal-familja ta' problemi tas-smigħ jew tinnitus? *

- o Iva
- o Le
- o Jekk iva, spjega:

Bidu ta 'tinnitus: Deskrizzjoni ta' meta tinnitus kien innutat għall-ewwel darba *

_____

Tip ta' tinnitus: Deskrizzjoni tal-ħoss *

- o Żanżin
- o Żarżir
- o Tisfir
- o Ihħammjar
- o Tektik
- o Ħoss ieħor:_____

It-tinnitus huwa kostanti jew intermittenti?*

- o Kostanti
- o Intermittenti

In-naħa tat-tinnitus: Fejn it-tinnitus huwiex prinċipalment preżenti *

- Mill-widna tax-xellug
- Mill-widna tal- lemin
- Miż-żewġ widnejn
- Mill- moħħ

Addattat minn Langguth et al. (2007). Tinnitus Sample Case History Questionnaire. Retrieved from tinnitusresearch.net/images/files/migrated/consensusdocuments/en/TINNITUS_SAMPLE_CASE_HISTORY_QUESTIONNAIRE.pdf

Appendix L: 4C Tinnitus Management Questionnaire

Tinnitus is the sensation of sound in the ears or head without any external sound source. It may sound like a buzzing, whistle, ringing, humming, pulsing or other types of sound.

Read the questions carefully and for each question choose a number that describes best your current level of confidence. You should choose a number from 0 to 10. 0 means you are "Not confident at all" in managing your tinnitus in the particular scenario described in the question and 10 means you are "Very confident".

1. How confident are you that you are able to carry out your day-to-day, even with tinnitus? *

Not confident at all

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10

Very confident

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10

2. How confident are you that you are able to rest and relax, even with tinnitus? * Not confident at all

Very confident

3. How confident are you that you can enjoy your life fully, even with tinnitus? * Not confident at all

- o 0
- o 1

- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10

Very confident

4. How confident are you that you can do all of the above without using any avoidance behaviour [eg. using background noise or avoiding certain situations]? *

Not confident at all

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10

Very confident

Retrieved from Aazh, H., Moore, B. C. J., & Lammaing, K. (2022). 4C Tinnitus Management Questionnaire. Retrieved from https://hashirtinnitusclinic.com/4c-tinnitus-management-questionnaire/

Appendix M: Validity of the Case History Form

The case history form was seen and analysed by the study's supervisor and a professional audiologist for face and content validity. In the table below the amendments are show.

Previous Question	**Amendments**
Do you suspect you have a hearing loss?	Removed as this was going to be tested.
With which ear do you hear best?	Removed as this was going to be tested.
Have you been exposed to occupational or recreational noise?	Changed to: Do you work in a noisy environment? Have you ever been exposed to loud noises for extended periods?
Have you had ear pain or drainage from your ears within the last 3 months?	Changed to: Brief overview of relevant conditions or past treatments: List of medications being taken:
Have you experienced dizziness, balance problems or falls?	
Are you currently being treated for emotional illness, behavioural illness, depression or substance abuse?	
Are there any other factors you believe may be relevant to your hearing or tinnitus?	Description of when tinnitus was first noticed:
Describe your tinnitus.	Onset of tinnitus: Description of when tinnitus was first noticed Description of the sound: Ringing, Hissing, Humming, Buzzing, Whistling, Other Is the tinnitus constant or intermittent? Side of tinnitus: Where the tinnitus is predominantly present: Right ear, Left ear, Both ears, Brain

Appendix N: Maltese 4C Tinnitus Management Questionnaire

‘Tinnitus’ huwa s-sensazzjoni ta ħoss fil-widnejn jew ir-ras mingħajr ebda sors ta' ħoss estern. Jista ikun ħoss bħal żanżin, żarżir, tisfir, iħħammjar, tektik jew tipi oħra ta' ħoss.

Aqra l-mistoqsijiet bir-reqqa u għal kull mistoqsija agħżel numru li jiddeskrivi l-aħjar il-livell attwali ta' kunfidenza tiegħek. Għandek tagħżel numru minn 0 sa 10. 0 ifisser li inti “Mhux kunfidenti” fil-ġestjoni tat- ‘tinnitus’ tiegħek fix-xenarju partikolari deskritt fil-mistoqsija u 10 ifisser li inti “Kunfidenti ħafna”

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10

1. Kemm int kunfidenti li int kapaċi twettaq il-ġurnata tiegħek, anke bit-‘tinnitus’? * Mhux kunfidenti

Kunfidenti ħafna

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9

- 10

2. Kemm int kunfidenti li kapaċi tistrieħ u tirrilassa, anke bit-‘tinnitus’? * Mhux kunfidenti

Kunfidenti ħafna

- 0
- 1
- 2
- 3

3. Kemm int kunfidenti li tista’ tgawdi ħajtek bis-sħiħ, anke bit-‘tinnitus’? * Mhux kunfidenti

- 4
- 5
- 6
- 7
- 8
- 9
- 10

Kunfidenti ħafna

4. Kemm int kunfidenti li tista' tagħmel dan kollu ta' hawn fuq mingħajr ma tuża xi mġiba ta' evitar [eż. tuża storbju fl-isfond jew tevita ċerti sitwazzjonijiet]? *

Mhux kunfidenti

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10

Kunfidenti ħafna

Addattat minn Aazh, H., Moore, B. C. J., & Lammaing, K. (2022). 4C Tinnitus Management Questionnaire. Retrieved from https://hashirtinnitusclinic.com/4c-tinnitus-management-questionnaire/

Appendix O: Permission for Use and Translation of 4C-TQ

Permission for Use and Translation of the 4C Tinnitus Questionnaire

Laura Mercieca

[redacted]

Dear [redacted]

My name is Laura Mercieca and I am a student at the University of Malta, reading for a Master's of Science in Audiology. I am presently conducting a research study for my dissertation titled 'Otoacoustic Emissions as a part of the Test Battery for Tinnitus Diagnosis, this is being supervised by Dr Nadine Tabone.

The aim of my study is to explore differences in OAEs in individuals with tinnitus and those without, whilst also analysing the correlation of subjective tinnitus measures and objective OAE measures. The assessment process will consist of administering a brief case history as well as a scaled tinnitus questionnaire, followed by a series of audiological tests including otoscopy, tympanometry, pure-tone audiometry, and distortion- product otoacoustic emissions.

I would therefore like to request permission to use the '4C Tinnitus Questionnaire' as part of this series of tests. Given the bilingual context of the population, I would also like to request permission to translate the tool into Maltese.

I look forward to hearing back from you.

Thank you and kind regards,

Laura Mercieca.

[redacted]

Dear Laura

Thanks for your email. Yes, that would be fine.

BW

[redacted]