A HYBRID HEARING PROTECTION AND COMMUNICATION SYSTEM: PROOF-OF-CONCEPT EVALUATION OF ACTIVE NOISE CANCELLATION, AMPLIFICATION, AND DIGITAL NOISE REDUCTION

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JUNE 2026

CERTIFICATE

This is to certify that this dissertation, entitled **A Hybrid Hearing Protection and Communication System: Proof-Of-Concept Evaluation of Active Noise Cancellation, Amplification, and Digital Noise Reduction,** is a bonafide work submitted in part fulfilment of the requirements for the degree of Master of Science (Audiology) of the student Registration number P01II24S023029. This has been carried out under the guidance of the faculty of this institute and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

Mysuru
June 2026

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CERTIFICATE

This is to certify that this dissertation, entitled **"A IIYBRID HEARING PROTECTION AND COMMUNICATION SYSTEM: PROOF-OF-CONCEPT EVALUATION OF ACTIVE NOISE CANCELLATION, AMPLIFICATION, AND DIGITAL NOISE REDUCTION",** has been prepared under my supervision and guidance. It is also being certified that this dissertation has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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DECLARATION

This is to certify that this dissertation, entitled entitled **A Hybrid Hearing Protection and Communication System: Proof-Of-Concept Evaluation of Active Noise Cancellation, Amplification, and Digital Noise Reduction** is the result of my own study under the guidance of Dr. P. Arivudai Nambi, Associate Professor, Department of Audiology, All India Institute of Speech and Hearing, Mysore and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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ABSTRACT

Conventional passive hearing protection devices attenuate hazardous noise but impair speech communication, limiting their effectiveness in industrial settings for both normal-hearing workers and those with sensorineural hearing loss. The present study developed and evaluated a proof-of-concept hybrid hearing protection and communication system integrating passive attenuation, active noise cancellation (ANC), and an envelope-preserving digital noise reduction (DNR) algorithm on a real-time platform. A total of 37 participants, 25 with mild to moderate sensorineural hearing loss and 12 with normal hearing, completed a Kannada sentence recognition task in industrial noise under four conditions: Gain Only, Gain + ANC, Gain + DNR, and the complete Hybrid (Gain + ANC + DNR). Insertion loss was additionally measured across six headset configurations using probe microphone recordings.

Findings revealed that the Hybrid condition produced the best speech-in-noise performance in both groups, outperforming Gain Only by 8.33 dB SNR in the hearing-impaired group and 6.24 dB SNR in the normal-hearing group. Gain + ANC and Gain + DNR each improved performance over Gain Only, but did not differ significantly from each other, indicating comparable individual benefit. The Hybrid condition significantly outperformed both, confirming an additive advantage when ANC and DNR were combined. Insertion loss measurements showed that the Hybrid configuration achieved the broadest noise attenuation across frequencies.

The study highlights that integrating ANC and an envelope-preserving DNR algorithm within a hearing protection platform produces meaningful speech intelligibility benefits beyond any single-component system, in both hearing-impaired and normal-hearing individuals. The findings support the development of personalised, multi-technology occupational hearing protectors as a clinically viable approach to address the dual demands of noise protection and workplace communication.

CHAPTER 1

INTRODUCTION

Exposure to industrial noise remains a significant occupational and public health challenge globally. The World Health Organisation (WHO, 2021) estimates that more than 430 million individuals worldwide experience disabling hearing loss, with a considerable proportion attributable to noise-induced hearing loss (NIHL) from occupational and environmental exposures. In the Indian context, Kumar et al. (2015) conducted a study involving 360 factory workers aged 20 to 55 years. They identified the NIHL prevalence of 49.45% based on pure-tone audiometry and 67% based on distortion-product otoacoustic emissions. The prevalence was notably elevated among workers aged over 40 years and those subjected to noise levels ranging from 91 to 100 dBA. These observations highlight that NIHL constitutes not only a global occupational health priority but also an urgent concern in rapidly industrialising economies such as India, where accelerated industrial growth has intensified the risk of hazardous workplace noise exposure.

Conventional hearing protection devices (HPDs), including earmuffs and earplugs, serve as the primary line of defence against hazardous occupational noise. Although these devices effectively attenuate harmful noise exposure, their inherent limitations are well established in the literature. Passive protection demonstrates reduced efficacy at low frequencies owing to the extended wavelength characteristics of industrial noise (Berglund et al., 1996). More critically, passive attenuation indiscriminately reduces both hazardous noise and essential auditory signals, including speech and warning sounds. Consequently, workers frequently experience communication difficulties and diminished situational awareness (Giguère & Laroche, 2011). This communication impediment often leads to noncompliance, as workers remove HPDs to facilitate interaction with colleagues or respond to environmental cues, thereby exposing themselves to unsafe noise levels.

Workers with pre-existing hearing impairment remain particularly vulnerable in such environments. Hearing loss associated with occupational noise exposure is typically permanent; hence, preventing additional auditory damage is essential to preserve residual hearing, communication ability, and overall quality of life (Alnoury et al., 2025; Nyarubeli et al., 2019). Importantly, longitudinal evidence indicates that noise-induced hearing loss (NIHL) may continue to progress, although at a slower rate. NIHL progresses even in workplaces implementing hearing conservation programs, highlighting the need for continuous protection throughout a worker's occupational lifespan (Lopes et al., 2024; Themann et al., 2023). Consequently, workers with hearing impairment still require effective hearing protection despite their reduced auditory sensitivity. However, conventional HPDs present a substantial challenge for this population. Because the HPDs indiscriminately attenuate environmental sounds, they further compromise access to speech, warning alarms, and other safety-critical auditory cues that are already difficult to perceive. This reduction in auditory accessibility can negatively affect communication, situational awareness, and ultimately compliance with hearing protection usage.

For individuals with pre-existing hearing impairment, amplification through hearing aids is necessary to maintain effective communication. However, conventional hearing aids amplify both speech signals and background noise, which compromises listening comfort and obscures important auditory cues such as warning alarms (Hétu, 1994; Dolan & Maurer, 1996). To address this challenge, digital noise reduction (DNR) algorithms have been developed, encompassing techniques such as spectral subtraction (Boll, 1979), Wiener filtering (Doclo & Moonen, 2002; Spriet et al., 2004), and modulation-based approaches (Chung, 2004). While these strategies enhance listening comfort, their contribution to speech intelligibility in complex industrial noise environments remains modest (Douglas & Sun, 2003; Sarampalis et al., 2009). Similarly, directional microphones and beamforming technologies can improve signal-to-noise ratio (SNR) under controlled conditions (Ricketts & Dhar, 1999; Luts et al., 2010), yet their performance is often limited in dynamic industrial settings.

Recent developments in machine learning have introduced more sophisticated approaches to noise reduction. Deep neural networks (Xu et al., 2015), recurrent architectures (Weninger et al., 2015), and transformer-based models (Chen et al., 2023) have demonstrated substantial improvements in speech quality and intelligibility across complex acoustic environments. Hybrid approaches combining deep learning with Wiener filtering and beamforming are emerging as robust solutions (Guevara et al., 2016; Westhausen et al., 2024). Despite their potential, these technologies remain largely confined to hearing aids and laboratory prototypes rather than occupational hearing protection systems.

Active noise cancellation (ANC) technologies have meanwhile demonstrated considerable effectiveness in attenuating low-frequency industrial noise that is inadequately controlled by passive protection alone. Adaptive feedback and feedforward ANC systems have achieved noise reduction levels of up to 30 dB and, when combined with amplification, have improved speech SNR by as much as 14 dB in noisy environments (Young et al., 2005). Commercial ANC earmuffs are extensively used in industrial and aviation settings. Nevertheless, most commercial systems do not incorporate amplification tailored for hearing-impaired individuals or advanced noise reduction capabilities for speech enhancement.

An examination of the commercial landscape reveals partial yet incomplete solutions. For instance, the SoundGear Phantom integrates custom-moulded earmuffs with hearing aid amplification and is FDA-registered as both a hearing aid and a hearing protector (SoundGear, Minnesota, USA). Tactical communication systems such as the 3M PELTOR ComTac and the Ops-Core AMP combine passive attenuation with environmental microphones and situational awareness features, primarily serving military and law enforcement applications (3M, Minnesota, USA; Gentex Corporation, Pennsylvania, USA). Recreational earmuffs such as the

Howard Leight Impact Pro amplify low-level sounds while attenuating impulsive noise; however, these devices lack true ANC capability (Honeywell, North Carolina, USA). While these products demonstrate the technical feasibility of integrating protection with communication functions, most incorporate only two of the three important components: passive attenuation, ANC, and noise-reduced amplification.

Prototype systems have demonstrated that the integration of hearing protection and communication enhancement within a single device is achievable. A collaborative research initiative between the National Institute for Occupational Safety and Health (NIOSH) and the University of Connecticut developed a circumaural hearing protection device incorporating two discrete digital signal processors (DSPs). One DSP was dedicated to subband active noise cancellation, while the second processor enhanced the communication channel. Evaluations of this system showed marked improvements in speech recognition scores in noise, even at sound pressure levels approaching 115 dBA, without compromising the detectability of important warning signals (Brammer et al., 2014; Lee et al., 2014). Earlier research involving electronic earmuffs, exemplified by the MineEars prototype, similarly confirmed that speech intelligibility benefits could be achieved when amplification parameters were appropriately regulated (Byrne & Palmer, 2012). Collectively, these investigations suggest that the integration of passive attenuation with ANC and adaptive gain control represents a promising approach to preserving hearing function while maintaining the audibility of essential communication signals.

1.2. Need for the Study

Despite advances in hearing aids, ANC earmuffs, and electronic communication headsets, no widely accessible system currently integrates passive attenuation, ANC, and advanced speech-enhancing amplification within a single platform optimized for hearing-impaired industrial workers. Existing technologies address only isolated aspects of the problem. Hearing aids improve audibility but perform inadequately in high-intensity industrial noise, ANC earmuffs effectively suppress low-frequency noise yet lack communication-oriented amplification, and electronic amplifying earmuffs generally rely on simple level-dependent amplification without sophisticated noise reduction capabilities. Consequently, industrial workers with hearing impairment continue to experience a compromise between adequate hearing protection and effective communication in noisy occupational environments.

This limitation is particularly important because hearing loss associated with occupational noise exposure is typically permanent, making preservation of residual hearing essential for maintaining communication ability and quality of life (Alnoury et al., 2025; Nyarubeli et al., 2019). Also, longitudinal evidence suggests that noise-induced hearing loss may continue to progress (Lopes et al., 2024; Themann et al., 2023). Hence, workers with hearing impairment require continuous hearing protection while simultaneously needing sufficient auditory access for safe communication and environmental awareness.

Although previous studies have independently evaluated hearing aids, ANC systems, and communication-enhancing earmuffs, limited research has systematically investigated the combined implementation of these technologies within a unified hearing protection platform for industrial applications. In particular, evidence remains limited regarding whether simultaneous integration of passive attenuation, ANC, and adaptive speech enhancement can improve communication without compromising access to target signals in high-noise environments.

Recent advances in adaptive noise reduction algorithms provided an opportunity to address this gap. Poluboina, Pulikala, and Nambi (2022) introduced a novel noise reduction technique designed to minimize mean squared error (MSE) between clean and enhanced speech envelopes. This approach adaptively shapes suppression according to envelope characteristics, thereby preserving perceptually significant cues while applying less aggressive attenuation compared to conventional Wiener filtering methods. Evaluations conducted using cochlear implant simulations demonstrated promising improvements in speech intelligibility outcomes. More recently, the algorithm was evaluated with individuals diagnosed with hearing impairment, demonstrating clear benefits for communication in noisy environments (Chethan & Nambi, 2025). These findings suggested that the algorithm could serve as a suitable candidate for integration within an occupational hearing protection framework.

Accordingly, the present study investigated the feasibility of a hybrid hearing protection system integrating passive earmuff attenuation, ANC, and adaptive noise-reduced amplification within a single platform. The study aimed to evaluate whether such an integrated approach could simultaneously support hearing protection and speech perception in noise. As a proof-of-concept investigation, this work sought to examine the practicality and potential benefits of combining envelope-preserving noise reduction with ANC-enabled hearing protection, an approach that has received limited systematic investigation in previous research.

1.3. AIM

This study aimed to develop and evaluate a proof-of-concept hybrid hearing protection system through the integration of passive attenuation, the built-in active noise cancellation capability of a commercial headset, and real-time amplification incorporating an envelope-preserving digital noise reduction algorithm.

1.4. Objectives of the Study

- To compare speech recognition in industrial noise across amplification-only, amplification with ANC, amplification with DNR, and amplification with combined DNR and ANC processing configurations.
- To measure and compare insertion loss across the different processing configurations using probe microphone measurements relative to the unprotected open-ear condition.

CHAPTER 2

REVIEW OF LITERATURE

2.1. Noise Exposure, Hearing Loss, and the Need for Hearing Protection

Chronic exposure to high-intensity industrial noise is a well-established cause of noise-induced hearing loss (NIHL). Occupational environments such as factories, workshops, and construction sites frequently expose workers to noise levels exceeding recommended safety limits, thereby increasing the risk of permanent auditory damage. The World Health Organization (WHO, 2021) identified occupational noise exposure as a major global public health concern associated with auditory and non-auditory health consequences. In India, Kumar et al. (2015) reported a high prevalence of NIHL among industrial workers, particularly among individuals above 40 years of age and those exposed to noise levels between 91 and 100 dBA.

Hearing protection devices (HPDs), including earplugs and earmuffs, are essential for preventing further auditory damage. Conventional passive HPDs provide broadband attenuation by physically blocking sound transmission to the ear canal. Although effective in reducing hazardous noise exposure, passive devices attenuate both unwanted noise and desirable acoustic signals such as speech and warning alarms, often resulting in communication difficulties and reduced situational awareness (Giguère & Laroche, 2011). These limitations may contribute to poor compliance, as workers often remove HPDs to facilitate communication, thereby increasing their risk of hazardous noise exposure. In addition to communication difficulties, prolonged reduction in auditory interaction may also contribute to feelings of social isolation, frustration, and reduced workplace participation. Over time, persistent communication barriers and listening difficulties may negatively affect psychological well-being and have been associated with increased stress, social withdrawal, and depressive symptoms among individuals exposed to occupational hearing difficulties.

2.2. Passive and Active Hearing Protection Devices

Passive Hearing Protection Devices

Passive HPDs rely on mechanical attenuation and are most effective at mid- and high-frequencies, whereas their performance at low frequencies is limited because of the longer wavelengths of low-frequency sounds (Berglund et al., 1996). Several studies have demonstrated that passive HPDs can significantly reduce speech intelligibility, particularly in noisy environments where speech cues are already degraded (Giguère & Laroche, 2011; Karami et al., 2020).

A study conducted in an industrial work environment in Iran evaluated speech intelligibility using moulded filtered earplugs, conventional earplugs, and earmuffs. Using Real-Ear Attenuation at Threshold (REAT) and Speech Discrimination Scores (SDS), the authors reported that although all HPDs reduced noise exposure, speech intelligibility varied considerably across devices, with filtered earplugs providing relatively better speech perception than conventional earplugs and earmuffs (Mohammadi et al., 2012). This study showed the trade-off between hearing protection and communication associated with passive HPDs.

Active Hearing Protection Devices

Active hearing protection devices incorporate electronic components to enhance situational awareness while maintaining protection from hazardous noise. These devices typically use external microphones and internal speakers to allow low-level environmental sounds to pass through while attenuating high-level noise.

Brown et al. (2015) compared active and passive HPDs using objective speech intelligibility measures and subjective ratings. Their findings demonstrated that active HPDs preserved speech perception more effectively than passive devices under certain listening conditions, particularly at moderate noise levels. Importantly, the authors controlled for passive attenuation by ensuring that both active and passive devices had comparable baseline attenuation levels, thereby allowing the specific benefits of active processing to be isolated.

Lin et al. (2005) evaluated an Active Feedback Active Noise Control (AFANC) headset designed to reduce low-frequency noise while maintaining speech audibility. Objective acoustic measurements and speech testing showed that the AFANC system provided additional low-frequency attenuation beyond passive protection alone without significantly degrading speech perception. This study provided early evidence that combining passive attenuation with active noise control (ANC) could address the limitations associated with traditional passive HPDs.

2.3. Active Noise Cancellation and Low-Frequency Noise Control

Industrial noise frequently contains substantial low-frequency components that are inadequately attenuated by passive HPDs. Active noise cancellation (ANC) systems address this limitation by generating anti-phase acoustic signals that cancel incoming low-frequency noise.

A foundational review presented at the International Commission on Biological Effects of Noise (ICBEN) conference examined the application of active noise control in hearing protectors. The review discussed feedforward and feedback ANC architectures and demonstrated that ANC systems could provide approximately 20–30 dB of additional attenuation at low frequencies, depending on system design characteristics (Morgan et al., 2008). However, the authors emphasized that ANC systems must be carefully designed to avoid compromising speech perception and sound localization abilities.

Young et al. (2005) reported that ANC-based hearing protectors improved speech signal-to-noise ratio (SNR) by up to 14 dB in low-frequency-dominated noise environments. These findings further support the potential of ANC technology to complement passive attenuation in industrial hearing protection systems.

2.4. Speech Intelligibility and Situational Awareness with HPDs

In addition to attenuation, effective HPDs must preserve speech intelligibility and situational awareness. Several studies have demonstrated that chronic noise exposure itself can adversely affect central auditory processing, even among individuals with normal audiometric thresholds.

A study comparing individuals with NIHL, noise-exposed individuals with normal hearing sensitivity, and non-noise-exposed controls evaluated speech intelligibility in noise with and without HPDs. The results demonstrated that HPDs had minimal additional negative effects on speech intelligibility in the NIHL and noise-exposed normal-hearing groups. In contrast, the control group exhibited greater reductions in intelligibility when HPDs were worn, particularly at poorer SNRs of −5, −10, and −15 dB. The authors concluded that chronic noise exposure may produce subclinical auditory processing deficits that affect speech perception even before measurable hearing loss becomes evident (Rocha et al., 2021).

More recently, Snapp et al. (2023) investigated situational awareness using a dual-task paradigm in listeners with simulated NIHL while wearing HPDs. Speech intelligibility, sound localization accuracy, and reaction time were measured simultaneously. The findings demonstrated that HPDs significantly affected spatial perception and increased reaction time, particularly in listeners with simulated hearing loss. These results emphasize the importance of evaluating HPDs beyond attenuation alone by incorporating measures of spatial hearing and cognitive listening demands.

Giguère et al. (2015) investigated the combined effects of varying degrees of sensorineural hearing loss and different control settings of level-dependent hearing protectors on speech recognition performance in noise. Using two commercial level-dependent devices (Peltor PowerCom Plus and Nacre QuietPro) tested in military noise environments with 45 participants grouped into four hearing profile categories (normal to moderate-to-severe hearing loss), the study demonstrated that passive attenuation alone severely degraded speech recognition in participants with hearing loss, with performance dropping to 0% in several cases among individuals with moderate-to-severe loss. Critically, the activation of level-dependent pass-through gain almost fully restored speech recognition for all hearing profile categories, and a higher gain setting was especially beneficial for individuals with greater hearing loss. These findings underscore the inadequacy of conventional passive HPDs for workers with hearing impairment and highlight the importance of incorporating individualised amplification within protective devices.

2.5. Listening Effort and Cognitive Load with Hearing Protection Devices

Although attenuation and speech intelligibility are the most commonly reported outcome measures in HPD research, listening effort, the cognitive resources required to perceive and process degraded auditory signals, has emerged as an important but under-investigated dimension of HPD performance. Even when speech recognition scores are maintained at acceptable levels under HPD use, increased listening effort may deplete cognitive resources and reduce overall performance in demanding work environments.

Smalt et al. (2020) examined the effects of four HPDs, two active (electronic) and two passive, on auditory situational awareness and listening effort in 13 normal-hearing participants under multiple background-noise conditions. Detection thresholds, sound localization accuracy, speech intelligibility, and cognitive load were assessed both with unoccluded ears and with each HPD. The findings demonstrated that, to varying degrees, all tested HPDs produced performance degradation relative to open-ear listening across most tasks. Of particular relevance was the finding that some HPDs significantly increased cognitive load, as measured by visual reaction time in a dual-task paradigm that combined working-memory demands with speech intelligibility. The authors concluded that situational awareness varies considerably across HPD types and that listening effort represents a critical but frequently overlooked dimension of HPD performance evaluation. These findings suggest that for workers required to monitor their environment, communicate, and perform complex cognitive tasks simultaneously, the type of HPD selected may substantially influence both safety and productivity beyond what attenuation metrics alone can indicate.

Taken together, the evidence indicates that the assessment of HPDs should extend beyond insertion loss and speech recognition scores to encompass cognitive and effort-related outcomes. This is particularly relevant for the development of hybrid hearing protection systems, in which the integration of amplification and noise reduction algorithms may alter not only the intelligibility of speech but also the perceptual effort required to process it.

2.6. HPD Compliance and Noncompliance Among Industrial Workers

The effectiveness of any hearing protection strategy depends critically on consistent and correct device usage. Despite widespread availability of HPDs in industrial settings, noncompliance remains a persistent and well-documented challenge. Workers frequently cite discomfort, communication interference, poor situational awareness, and perceived inconvenience as primary reasons for removing or improperly wearing their devices (Giguère & Laroche, 2011). Understanding the determinants of HPD use behaviour is essential for designing protection systems that workers will accept and consistently wear.

Fauzan et al. (2023) conducted a systematic literature review following PRISMA guidelines to identify factors influencing HPD usage among industrial workers. From an initial pool of 196 articles, 28 studies published between 2006 and 2021 met inclusion criteria. The review identified five major thematic categories influencing HPD use: sociodemographic factors (29%), cognitive-perceptual factors (29%), situational influences (18%), interpersonal influences (18%), and health-promoting behaviour (6%). Key barriers included inadequate perceived benefit, discomfort, poor fit, low perceived risk, and lack of organisational support, while facilitators included training, supervisory influence, and positive safety climate. The authors highlighted that perceived comfort and communication utility of HPDs were among the most modifiable determinants of consistent use, suggesting that devices that minimise communication impairment and discomfort are more likely to achieve sustained compliance.

These findings have direct implications for the design of hybrid hearing protection systems. A device that preserves or enhances communication while providing adequate noise attenuation directly addresses the most commonly cited barriers to consistent HPD use. The development of systems integrating active noise cancellation and speech-preserving amplification may not only improve auditory outcomes but also contribute to higher rates of device adoption and sustained wear in occupational environments.

2.7. Conceptual and Commercial Developments in HPDs

Several commercial devices have attempted to integrate hearing protection with amplification technologies. Abrams (2017) discussed the application of hearing-aid signal-processing principles to hearing protection, highlighting features such as level-dependent gain, compression, and noise-management strategies. Although this work did not report experimental outcome data, it provided an important conceptual framework for the development of hybrid HPDs.

Commercial systems such as the SoundGear devices developed by Starkey incorporate amplification within protective earmuffs and are marketed as solutions for individuals with hearing loss in noisy environments. Although white papers and manufacturer documentation describe the design concepts underlying these devices, peer-reviewed evidence evaluating their performance in industrial noise environments remains limited.

The reviewed literature demonstrates that passive HPDs effectively reduce hazardous noise exposure but frequently compromise speech communication and situational awareness. Active HPDs and ANC systems have shown improvements in low-frequency attenuation and speech audibility; however, most commercially available devices integrate only selected technological components. Research conducted in military, industrial, and laboratory settings highlights the need for unified systems that combine passive attenuation, ANC, and advanced signal-processing strategies tailored for individuals with hearing loss. Evidence on listening effort further indicates that effective HPD design must consider cognitive load alongside acoustic performance, as even devices that maintain adequate speech recognition may impose substantial mental effort demands that undermine worker safety and productivity (Smalt et al., 2020). Compliance research additionally underscores that devices perceived as impairing communication are less likely to be worn consistently, irrespective of their attenuation performance (Fauzan et al., 2023).

Despite promising prototypes and conceptual developments, there remains a lack of systematic evaluation of hybrid hearing protection systems that integrate passive attenuation, ANC, and advanced signal-processing features within a single platform for industrial workers with sensorineural hearing loss. This gap provides the foundation for the present study.

CHAPTER 3

METHOD

3.1. Participants

The present study included a total of 37 participants divided into two groups. Group I consisted of 25 individuals diagnosed with mild to moderate sensorineural hearing loss, with a mean age of 55.8 years (SD = ±3.61). Group II consisted of 12 individuals with normal hearing sensitivity, with a mean age of 24.5 years (SD = ±2.4).

Informed consent was obtained from all participants before data collection. The study adhered to the ethical standards outlined in the document Ethical Principles for Bio-Behavioural Research Involving Human Subjects (Venkatesan & Basavaraj, 2023). Ethical approval for the study was obtained from the Institutional Review Board of the All India Institute of Speech and Hearing on 06/01/2026 (Reference Number: SH/IRB/M.4/AUD.42/2025-26).

3.1.1. Inclusion and exclusion Criteria of group 1 (Hearing-impaired group):

Inclusion criteria

- Pure tone average (PTA) ranging between 26 and 55 dB HL, corresponding to mild to moderate bilateral sensorineural hearing loss. Figure 3.1 and Figure 3.2 illustrate the mean air conduction thresholds of the right and left ears of the participants, respectively.
- Speech Identification Scores (SIS) proportionate to the degree of hearing loss.
- Normal middle ear function as assessed using impedance audiometry with Type A tympanogram, characterized by middle ear peak pressure ranging from +60 to −100 daPa and admittance values ranging from 0.4 to 1.75 ml, obtained using a 226 Hz probe tone.

- Native speakers of Kannada.

Figure 3.1

Mean and SD of air conduction (AC) thresholds of the right ear.

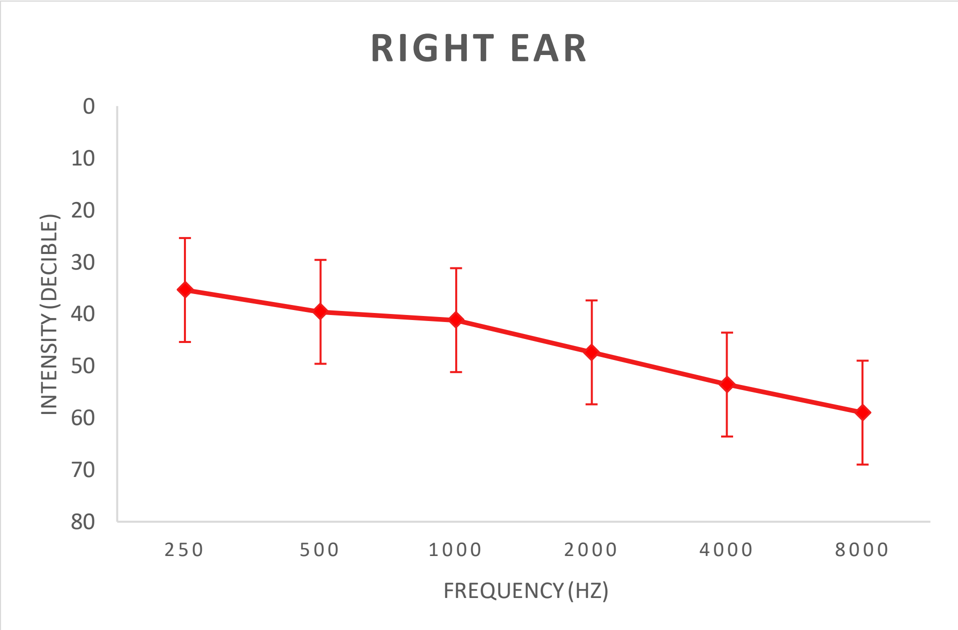
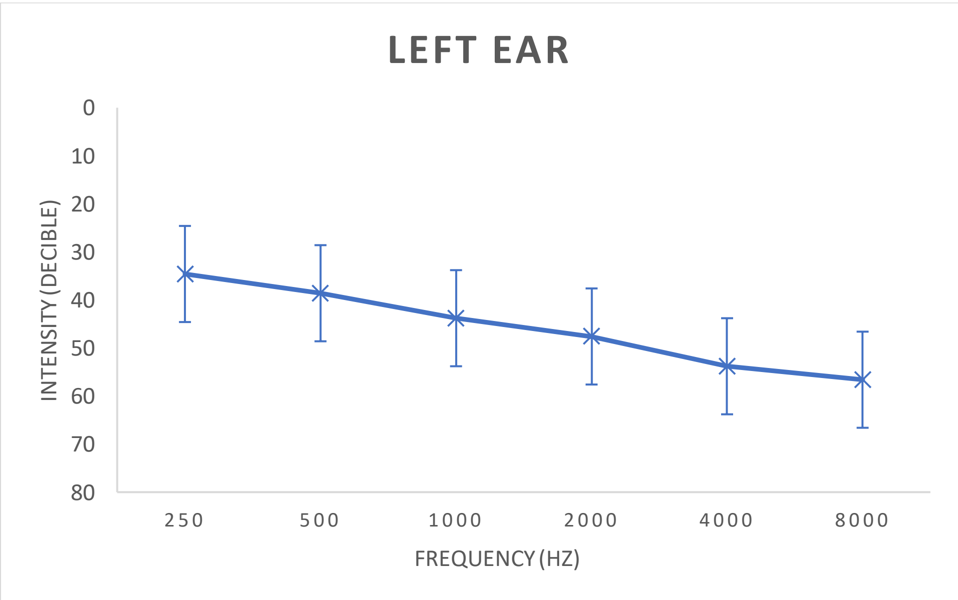


Figure 3.2

Mean and SD of air conduction (AC) thresholds of the left ear.



Exclusion criteria

- Presence of conductive, mixed, or unilateral hearing loss.
- Moderately Severe to profound hearing loss (>55 dB HL).
- History of chronic ear pathology, ear surgery, or recurrent ear infections.
- Presence of neurological, cognitive, or psychological conditions that could interfere with understanding instructions or completing the experimental tasks.
- Individuals using hearing aids incompatible with the study apparatus.
- Unwillingness to participate in the study or inability to provide informed consent.

3.1.2. Inclusion and Exclusion Criteria of Group II (Normal Hearing group):

Inclusion criteria

- Pure tone air conduction thresholds within normal limits (≤15 dB HL) at octave frequencies from 250 Hz to 8 kHz bilaterally.
- Normal middle ear function as evidenced by Type A tympanogram.
- Native speakers of Kannada.
- No history of otological or neurological disorders affecting hearing.

Exclusion criteria

- Pure tone thresholds greater than 15 dB HL (>15 dB HL) at any test frequency from 250 Hz to 8 kHz.
- Presence of conductive, mixed, or unilateral hearing loss.
- History of chronic ear pathology, ear surgery, or recurrent ear infections.

- Presence of neurological, cognitive, or psychological conditions that could interfere with understanding instructions or completing the experimental tasks.

- Unwillingness to participate in the study or inability to provide informed consent.

3.2. Test Environment

The study was carried out in a sound-treated room designed to maintain ambient noise levels within permissible limits as specified by the American National Standards Institute (ANSI, 2013). The acoustic environment was controlled throughout the experimental procedures to minimize the influence of external noise and reverberation on the obtained measures.

Experimental stimuli were presented under calibrated listening conditions. Broadband pink noise was employed during insertion loss measurements. Recorded industrial machinery noise combined with speech stimuli was used during speech perception testing in noise to simulate realistic occupational acoustic conditions. The stimuli were calibrated to the desired presentation levels using a sound level meter (SLM) before testing.

3.2.1 Equipment

Sennheiser HD 560S over-the-ear headphones are equipped with active noise cancellation (ANC). The headset microphones captured environmental signals, which were transmitted to a personal computer through wired connectivity for signal processing and presentation. MedRx audiological system for the assessment of real-ear benefit and insertion loss measurements. Personal computer (PC) equipped with digital signal processing software and an audio interface for stimulus presentation and signal control. A sound level meter (SLM) is used to verify and monitor stimulus input level during testing.

3.3. Stimulus

The stimuli used in the present study consisted of speech and noise materials. Speech perception testing was carried out using standard Kannada sentences obtained from the Kannada Sentence Identification Test developed by Geetha et al. (2014). The recorded sentence materials were presented under controlled listening conditions through the experimental setup. Noise stimuli included broadband pink noise and industrial noise recordings. Broadband pink noise was utilized for insertion loss measurements, whereas industrial noise stimuli were used during speech perception testing in noise. The industrial noise samples consisted of factory and workshop ambience, including machinery hum, alarms, and mixed industrial activity, and were obtained from publicly available sound libraries. The recordings were RMS-normalised before presentation and were delivered at an average intensity level of 75 dB(A), representative of typical industrial listening environments. Previous occupational studies have reported that industrial noise levels commonly range between 75 and 85 dB(A) (Kumar et al., 2015; NIOSH, 2024), thereby supporting the ecological validity of the selected stimuli.

3.4 Experimental Conditions

3.4.1. Experimental Conditions for Speech Perception in Noise

Participants were evaluated under four listening conditions. Passive noise reduction and gain were present in all conditions. The listening conditions differed only in the activation of Active Noise Cancellation (ANC) and Digital Noise Reduction (DNR):

1. Gain Only
2. Gain + ANC
3. Gain + DNR
4. Gain + ANC + DNR (Hybrid)

3.4.2. Experimental Conditions for Insertion Loss Measurement

Insertion loss measurements were obtained under six experimental conditions. Passive attenuation provided by the headset was present in all conditions. The experimental conditions differed in the activation of Active Noise Cancellation (ANC), gain, and the envelope-preserving Digital Noise Reduction (DNR) algorithm:

1. Passive Only
2. ANC Only
3. Gain Only
4. Gain + ANC
5. Gain + DNR
6. Gain + ANC + DNR (Hybrid)

3.5 Signal Processing Chain

The signal-processing framework employed in the present study is illustrated in Figure 3.5. The experimental system consisted of a hybrid headset incorporating passive attenuation and active noise cancellation (ANC), connected to a laptop for real-time digital signal processing. Speech signals and environmental industrial noise were captured through the headset microphones and transmitted to the laptop, where digital noise reduction and hearing-aid amplification algorithms were implemented. The processed signal was subsequently delivered to the listener through the headset earphones.

Digital Noise Reduction

The first stage of processing involved the envelope-preserving digital noise reduction (DNR) algorithm. Before speech processing, approximately 2 seconds of environmental noise were captured and analyzed to estimate the spectral characteristics of the background noise. This initial noise profile served as the reference for subsequent adaptive noise reduction.

Following noise profile estimation, the incoming signal was processed in frames of 512 samples with 50% overlap (256 samples) to facilitate real-time operation while maintaining temporal continuity between successive frames. For each frame, the signal spectrum was analyzed and the signal-to-noise ratio (SNR) was estimated using the previously obtained noise profile. Based on the estimated SNR, an adaptive gain function was applied to attenuate noise-dominant frequency components while preserving speech-dominant components. The algorithm was designed to preserve the temporal envelope of speech, thereby minimizing distortion of important speech cues while reducing background noise. The processed frames were subsequently recombined using an overlap-add procedure to generate a continuous enhanced speech signal.

Hearing-Aid Amplification

Following digital noise reduction, the enhanced signal was routed to the 12-channel hearing-aid amplification algorithm. The amplification algorithm was adapted from the signal-processing framework described by Kumar and Nambi (2024). Frequency decomposition was performed using a bank of 128^{th} order finite impulse response (FIR) filters that separated the signal into multiple frequency bands. The centre and corner frequencies of the bands were determined using Greenwood's function (Greenwood 1991). Within each frequency band, signal levels were estimated using an envelope detector with an attack time of 5 ms and a release time of 70 ms. Envelope tracking was achieved through low-pass filtering, allowing accurate estimation of signal levels for dynamic range compression.

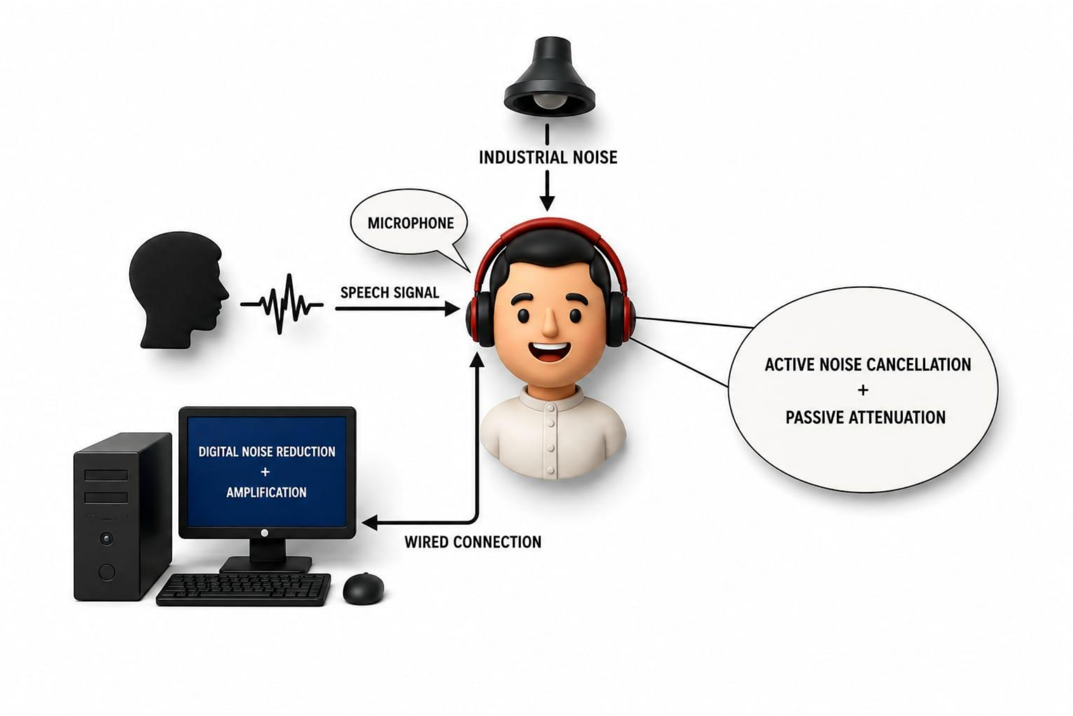
Gain values were prescribed according to the NAL-NL2 fitting rationale and implemented on a frame-by-frame basis across the frequency bands. Compression thresholds and compression ratios were derived from the prescribed fitting parameters and applied to ensure audibility while maintaining listening comfort. The amplified signal was then converted back to the time domain and delivered through the headset earphones. Throughout the processing chain, efforts were made to minimize end-to-end latency to enable real-time operation.

The headset provided passive noise reduction through its circumaural design and mechanical construction. Passive attenuation was achieved by components such as the earcup enclosure, foam cushions and seal, headband tension, and internal damping materials, which together reduced the transmission of external sound into the ear canal. This passive attenuation primarily contributed to broadband reduction of environmental noise, particularly in the mid- and high-frequency regions.

In addition to passive attenuation, active noise cancellation (ANC) was incorporated through the electronic processing capabilities of the headset. The ANC system utilises external reference microphones to capture incoming environmental noise and internal microphones positioned near the ear canal to monitor residual noise within the earcup. Adaptive filtering algorithms generated phase-inverted anti-noise signals, which were delivered through the headset drivers to reduce low-frequency environmental noise. Feedforward ANC utilized the external microphones to predict and attenuate incoming noise, whereas feedback ANC refined the cancellation process within the earcup using internal error monitoring. Thus, passive attenuation and ANC operated simultaneously, with passive mechanisms providing broad-spectrum attenuation and ANC primarily targeting low-frequency noise components.

Figure 3.5.

Signal-processing framework of the experimental hybrid headset system incorporating digital noise reduction, hearing-aid amplification, active noise cancellation, and passive attenuation.



3.6 Procedure

3.6.1. Noise Attenuation – Insertion Loss Measurement

The attenuation performance of the experimental system was evaluated to determine the effectiveness of the hybrid device in reducing external noise under different operating conditions. Measurements were carried out following the protocols recommended by ANSI S12.6-2016 and ISO 4869-2:2018.

Participants were seated in a sound-treated room and were instructed to wear the Sennheiser HD560S headset throughout the testing procedure. A probe microphone connected to the MedRx system was inserted into the ear canal and positioned within approximately 5 mm of the tympanic membrane to record in-ear sound pressure levels. Experimental stimuli consisted of broadband pink noise presented through calibrated loudspeakers under controlled listening conditions. Stimuli were presented at intensity levels of 65dB SPL.

Insertion loss measurements were obtained under six different headset configurations. For each condition, attenuation was quantified as insertion loss, calculated as the difference between the unaided and aided in-ear sound pressure level responses measured with the probe microphone across frequencies. Frequency-specific insertion loss values were obtained and averaged across participants for further analysis.

3.6.2. Speech Perception in Noise

Speech perception in noise was assessed using Kannada sentence recognition tasks presented in the presence of recorded industrial machinery noise. The background noise was maintained at a fixed presentation level of 75dBSPL to simulate realistic occupational listening conditions, while the level of the target speech signal was adaptively varied to determine speech recognition performance in noise.

Testing was carried out under four experimental listening conditions. Participants were instructed to listen carefully to each sentence and repeat verbally what they heard. The test began with the presentation of sentences at a -10dB SNR (65dBSPL), following which the SNR was adaptively modified based on participant responses. An adaptive staircase procedure with a 2 dB step size was employed throughout testing. Following a correct response, the SNR for the subsequent sentence was decreased by 2 dB, whereas following an incorrect response, the SNR was increased by 2 dB. This adaptive tracking procedure continued until the sentence list was completed and enabled estimation of the SNR corresponding to approximately 50% sentence recognition performance.

CHAPTER 4

RESULTS

All statistical analyses were conducted using RStudio. The modelling and diagnostic workflow employed the following packages: ‘glmmTMB’ for fitting generalized linear mixed models (GLMMs), ‘car’ for Wald chi-square tests, ‘DHARMa’ for residual diagnostics and assumption checks, and ‘emmeans’ for computing estimated marginal means (EMMs) and conducting pairwise comparisons. A GLMM was fitted with a fixed effect for the Hearing Protection Device (HPD) condition and a random intercept for Patient (PatientID). The analysis sequence involved model fitting, evaluation of model fit indices, diagnostic checks (uniformity, dispersion, and homogeneity of variance), significance testing of fixed effects using Type II Wald chi-square tests, and post-hoc pairwise comparisons using EMMs with Bonferroni correction to explore condition-wise differences.

4.1. Hearing Impaired

A Gaussian Generalized Linear Mixed Model (GLMM) with an identity link was fit to the SRTn data, featuring a fixed effect for the HPD condition and a random intercept for PatientID. Model fit statistics (AIC = 517.2, BIC = 532.9, and log-likelihood = –252.6) suggested an adequate fit. Residual diagnostics using the DHARMa package confirmed that there were no major violations of model assumptions. The Kolmogorov–Smirnov test for residual uniformity ($D = 0.052$, $p = 0.950$) indicated that the residuals were uniformly distributed. The dispersion test also showed no evidence of over-dispersion or under-dispersion (dispersion = 1.018, $p = 0.792$). Additionally, Levene’s test analog confirmed homogeneity of variance across the HPD groups ($F(3, 96) = 0.380$, $p = 0.768$). Based on these results, no additional dispersion term was included in the final model.

Type II Wald chi-square tests were used to investigate the main effect of the HPD condition on SRTn. Analysis of the fixed effects revealed a highly significant main effect of the HPD condition ($\chi^2(3) = 160.29$, $p < .001$). This result suggests that SRTn was significantly influenced by the specific device processing setting applied.

Given the significant main effect, pairwise comparisons with a Bonferroni adjustment were conducted to evaluate differences in SRTn across the four HPD conditions (Gain+DNR+ANC, Gain+DNR, Gain+ANC, and Gain only). The results demonstrated that every HPD condition differed significantly from one another. The Gain+DNR+ANC condition yielded the lowest overall SRTn (EMM = 74.1), which was significantly lower than Gain+ANC (estimate = –3.02, $p < .001$), Gain+DNR (estimate = –5.08, $p < .001$), and Gain only (estimate = –8.33, $p < .001$). Conversely, the Gain only condition resulted in the highest SRTn (EMM = 82.4) and was significantly greater than both Gain+ANC (estimate = 5.31, $p < .001$) and Gain+DNR (estimate = 3.25, $p < .001$). Finally, the Gain+ANC condition resulted in significantly lower SRTn values compared to the Gain+DNR condition (estimate = –2.06, $p = 0.014$).

Figure 4.1.

Mean speech reception threshold in noise (SRTn; dB) across the four HPD configurations for the Hearing-impaired group. Error bands represent ±1 standard deviation.

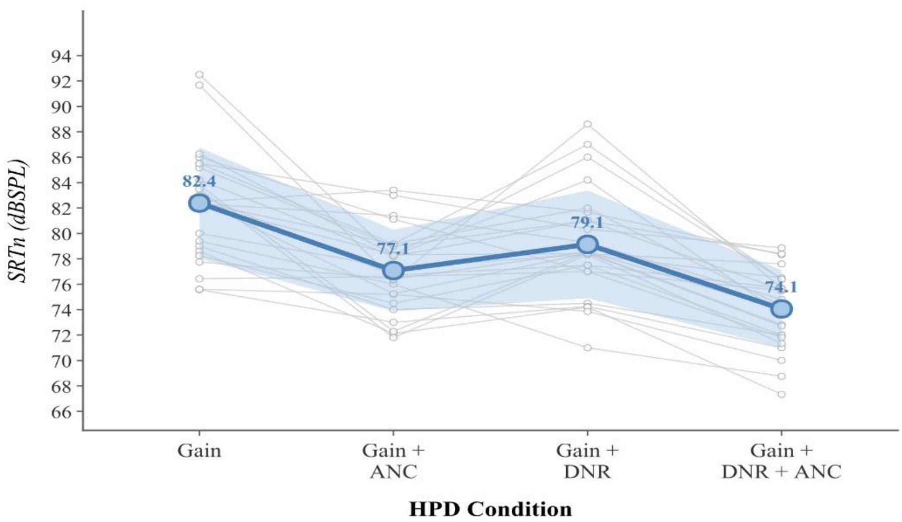


Table 4.1

Estimates and p-values of the pairwise comparison of SRTn (dB) across four HPD configurations for the hearing-impaired group

Condition	**Comparison**	**Estimate**	**p-value**
Gain only	Gain + ANC	5.31	<.001
	Gain + DNR	3.25	<.001
	Gain + ANC + DNR (Hybrid)	8.33	<.001
Gain + ANC	Gain + DNR	-2.06	.014
	Gain + ANC + DNR (Hybrid)	3.02	<.001
Gain + DNR	Gain + ANC + DNR (Hybrid)	5.08	<.001

Note: Negative estimates indicate lower SRTn in the first-listed condition relative to the comparison condition

4.2. Normal Hearing

A Gaussian Generalized Linear Mixed Model (GLMM) with an identity link was fit to the SRTn data, featuring a fixed effect for the HPD condition and a random intercept for PatientID. Model fit statistics (AIC = 210.0, BIC = 221.2, and log-likelihood = −99.0) suggested an adequate fit. Residual diagnostics using the DHARMa package confirmed that there were no major violations of model assumptions. The Kolmogorov–Smirnov test for residual uniformity ($D = 0.121$, $p = 0.485$) indicated that the residuals were uniformly distributed. The dispersion test also showed no evidence of over-dispersion or under-dispersion

(dispersion = 1.058, $p = 0.736$). Additionally, Levene's test confirmed homogeneity of variance across the HPD groups ($F(3, 44) = 0.400$, $p = 0.754$). Based on these results, no additional dispersion term was included in the final model.

Type II Wald chi-square tests were used to investigate the main effect of the HPD condition on SRTn. Analysis of the fixed effects revealed a highly significant main effect of the HPD condition ($\chi^2(3) = 99.52$, $p < .001$). This result suggests that SRTn was significantly influenced by the specific device processing setting applied.

Given the significant main effect, pairwise comparisons with a Bonferroni adjustment were conducted to evaluate differences in SRTn across the four HPD conditions (Gain+DNR+ANC, Gain+DNR, Gain+ANC, and Gain only). The Gain+DNR+ANC condition yielded the lowest overall SRTn (EMM = 67.9), which was significantly lower than Gain+ANC (estimate = −1.94, $p = .015$), Gain+DNR (estimate = −3.14, $p < .001$), and Gain only (estimate = −6.24, $p < .001$). Conversely, the Gain only condition resulted in the highest SRTn (EMM = 74.1) and was significantly greater than both Gain+ANC (estimate = 4.30, $p < .001$) and Gain+DNR (estimate = 3.10, $p < .001$). However, the Gain+ANC and Gain+DNR conditions did not differ significantly from each other (estimate = −1.20, $p = .375$), indicating that both conditions conferred comparable benefit when applied independently.

Figure 4.2.

Mean speech reception threshold in noise (SRTn; dB) across the four HPD configurations for the normal-hearing group. Error bands represent ±1 standard deviation.

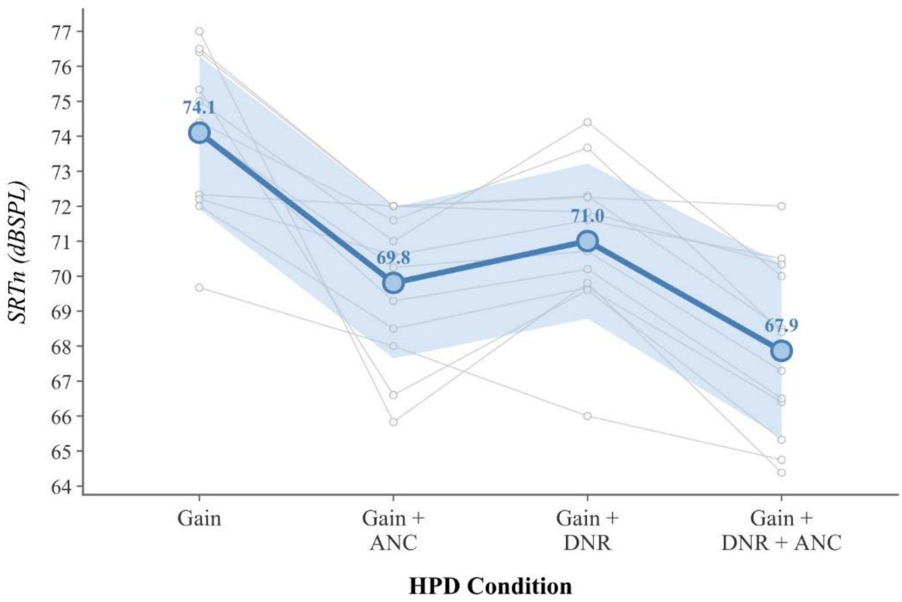


Table 4.2.

Estimates and p-values of the pairwise comparison of SRTn (dB) across four HPD configurations for the Normal hearing group

Condition	**Comparison**	**Estimate**	**p-value**
Gain only	Gain + ANC	4.30	<.001
	Gain + DNR	3.10	<.001
	Gain + ANC + DNR (Hybrid)	6.24	<.001
Gain + ANC	Gain + DNR	-1.20	.375
	Gain + ANC + DNR (Hybrid)	1.94	.015

Gain + DNR	Gain + ANC + DNR (Hybrid)	3.14	<.001

Note: Negative estimates indicate lower SRTn in the first-listed condition relative to the comparison condition

4.3. Insertion Loss: Hearing-Impaired Group

Insertion loss, defined as the difference in in-ear sound pressure level (SPL) between unaided and aided conditions measured by probe microphone at the tympanic membrane, was evaluated across six headset configurations in the hearing-impaired group. The analysis was descriptive in nature and focused on characterising the frequency-specific attenuation profile produced by each successive configuration.

In the Passive Only condition, in which ANC, gain, and DNR were disabled, and only the physical earcup was in place, the headset provided its baseline mechanical attenuation, determined entirely by the acoustic properties of the circumaural earcup. Insertion loss was greatest in the mid- and high-frequency regions, consistent with the circumaural design of the Sennheiser HD 560S. At low frequencies (125–250 Hz), passive attenuation was comparatively limited, reflecting the well-established physical constraint that mechanical barriers are less effective against sounds with longer acoustic wavelengths (Berglund et al., 1996).

When ANC Only condition was enabled, a clear and substantial increase in insertion loss was observed at low frequencies, particularly at 125 and 250 Hz. This improvement represents the targeted operating range of the ANC system, which generates adaptive anti-phase signals to cancel incoming low-frequency noise. Above approximately 1000 Hz, ANC contributed minimally to the insertion loss profile, as passive attenuation remained dominant in the mid- and high-frequency regions.

The Gain Only condition demonstrated a markedly reduced insertion loss relative to the Passive Only condition, particularly at low and mid frequencies. This reduction reflects the large NAL-NL2 prescribed gain applied to the hearing-impaired group. Because the amplification stage increases the in-ear SPL considerably across frequencies where hearing thresholds are elevated, the measured difference between unaided and aided in-ear levels is substantially narrowed. This finding does not imply reduced noise protection in a hazard sense; rather, it reflects the trade-off inherent in restoring speech audibility within the earcup for a population requiring substantial gain.

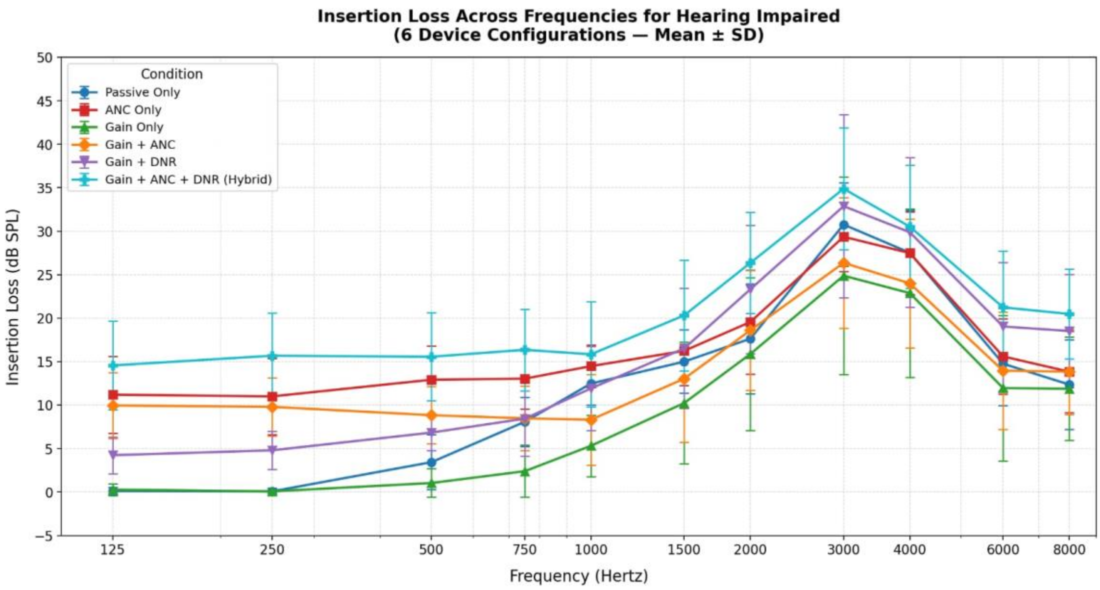
The ANC + Gain condition produced a combined attenuation profile that partially recovered the low-frequency insertion loss reduced in the Gain condition. Because ANC attenuates acoustic noise at the ear canal before it enters the amplification stage, it partially offsets the gain-induced reduction in net insertion loss at low frequencies. The result was a more balanced insertion loss curve across the frequency range compared with the Gain condition.

In the DNR + Gain condition, the insertion loss profile closely resembled that of the Gain condition at low frequencies, as DNR operates on the processed signal and does not directly alter the physical noise level at the ear canal. However, a modest increase in insertion loss was observed in the mid-frequency region relative to the Gain condition, attributable to the noise suppression action of the envelope-preserving DNR algorithm on the processed signal before its delivery to the listener.

The Hybrid System (ANC + DNR + Gain) produced the most favourable overall insertion loss profile across all tested frequencies. The simultaneous action of passive attenuation, ANC-mediated low-frequency cancellation, and DNR-mediated noise suppression yielded cumulative noise reduction spanning the full frequency range. Although the gain component necessarily introduced some reduction in net insertion loss relative to non-amplified configurations, the overall insertion loss in the Hybrid System substantially exceeded the unaided reference at all tested frequencies, confirming that the system maintained a meaningful protective function throughout the frequency range.

Figure 4.3.

Mean insertion loss (dB) as a function of frequency for the hearing-impaired group under six headset configurations: Passive Only; ANC only; Gain Only; Gain + ANC; Gain + DNR; and Gain + ANC + DNR (Hybrid). Higher insertion loss values indicate greater noise attenuation. The Hybrid configuration demonstrates the most detailed attenuation profile across the tested frequency range.



4.4. Insertion Loss: Normal-Hearing Group

Insertion loss measurements in the normal-hearing group followed a pattern broadly consistent with that observed in the hearing-impaired group across the Passive Only and ANC Only conditions. The Passive Only condition provided the same frequency-dependent attenuation profile as that observed in the hearing-impaired group, confirming that the inherent mechanical attenuation of the headset is primarily determined by the acoustic characteristics of the device rather than participant-specific factors such as hearing status. The ANC Only condition similarly extended insertion loss into the low-frequency region, with a comparable increase in attenuation at 125–250 Hz.

A meaningful difference between the two groups emerged in the gain-inclusive conditions. Unlike the hearing-impaired group, in whom the NAL-NL2 prescribed gain resulted in a substantial reduction in insertion loss across low and mid frequency regions, the normal hearing group demonstrated a considerably smaller reduction. This is because NAL-NL2 prescribes minimal gain for listeners with normal hearing thresholds; consequently, the amplification stage contributed little additional sound pressure level within the earcup. As the prescribed gain was smaller, the offset of passive attenuation by amplification was correspondingly less pronounced, and the net insertion loss in the Gain condition remained closer to that observed in the Passive Only condition.

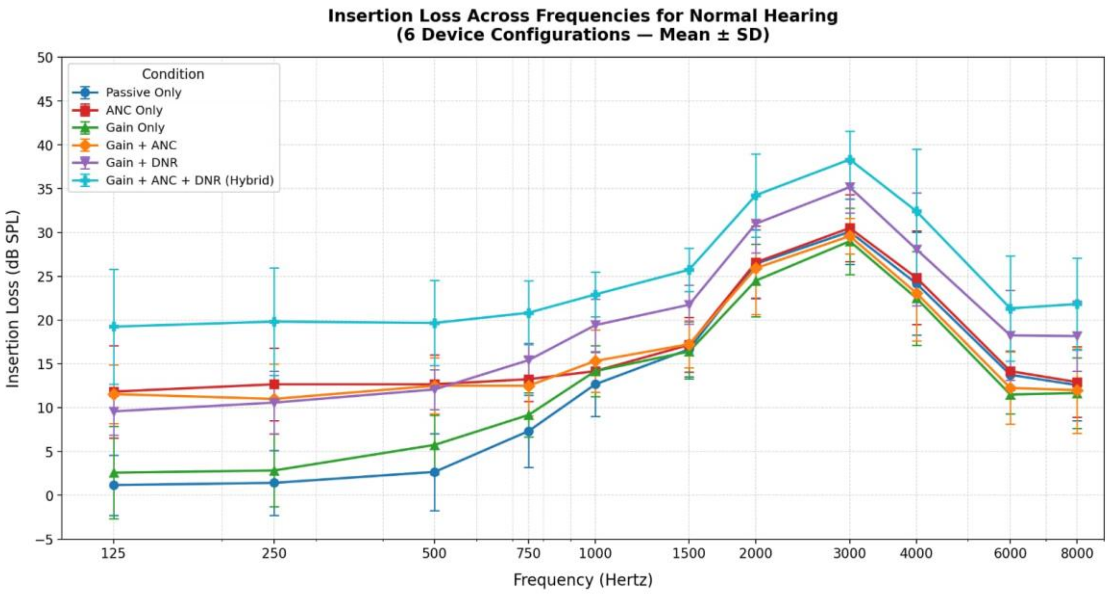
In the ANC + Gain condition, the addition of ANC partially compensated for the reduction in low frequency insertion loss associated with gain, resulting in a more favourable attenuation profile than that observed in the Gain only condition. The benefit was most evident in the low frequency region, where ANC is most effective.

In the DNR + Gain condition, mid frequency insertion loss demonstrated a modest improvement relative to the Gain only condition, consistent with the noise suppression effect of the envelope preserving DNR algorithm. Similar to the hearing-impaired group, DNR did not directly alter the physical attenuation provided by the headset but contributed to a reduction in the processed noise components delivered to the listener.

The Hybrid System (ANC + DNR + Gain) produced the most detailed insertion loss profile across all tested frequencies. The combined action of passive attenuation, ANC mediated low frequency noise cancellation, and DNR based noise suppression provided the greatest overall attenuation. These findings confirm that the integrated hybrid system offers the most effective broadband noise reduction while maintaining the prescribed gain required for auditory signal presentation.

Figure 4.4.

Mean insertion loss (dB) as a function of frequency for the normal-hearing group under six headset configurations: Passive Only; ANC only; Gain Only; Gain + ANC; Gain + DNR; and Gain + ANC + DNR (Hybrid). The pattern closely mirrors that of the hearing-impaired group, with the Hybrid condition providing the broadest attenuation profile.



CHAPTER 5

DISCUSSION

The present study investigated the effectiveness of a proof-of-concept hybrid hearing protection and communication system that integrated passive earmuff attenuation, active noise cancellation (ANC), and an envelope-preserving digital noise reduction (DNR) algorithm within a single real-time platform. Speech perception in noise was assessed under four conditions in both a hearing-impaired group and a normal-hearing group. The findings are discussed below with reference to the reported literature.

5.1. Effect of Noise Reduction Condition on Speech Perception in Noise

The Gain Only condition, in which passive attenuation and NAL-NL2 amplification were applied without any active noise management, consistently yielded the highest SRTn, reflecting the poorest speech-in-noise performance in both groups. This outcome is consistent with the known limitation of passive hearing protectors: although they reduce the overall sound pressure level at the ear, they attenuate both noise and speech indiscriminately, leaving the effective signal-to-noise ratio largely unchanged at the listener's eardrum (Giguère & Laroche, 2011). The addition of amplification through NAL-NL2 prescription restores the audibility of the attenuated speech signal; however, background noise is similarly amplified, and without an active noise management stage, the perceptual SNR advantage remains minimal.

The significant improvement observed in the Gain+ANC condition relative to Gain Only in both groups supports the role of active noise cancellation in reducing energetic masking of speech. ANC operates by generating phase-inverted anti-noise signals that destructively interfere with incoming noise at the ear canal, principally targeting the low-frequency components of industrial noise that are inadequately attenuated by passive mechanisms. By reducing the low-frequency noise floor before the signal reaches the amplification stage, ANC improves the effective SNR delivered to the listener, thereby facilitating speech recognition. In addition, attenuation of low-frequency noise may reduce the upward spread of masking, allowing important mid- and high-frequency speech cues to remain more accessible to the listener. This mechanism may be particularly beneficial for individuals with hearing impairment, who often exhibit reduced frequency selectivity and increased susceptibility to masking effects. The present findings are consistent with the reports of Young et al. (2005), who demonstrated SNR improvements of up to 14 dB in ANC-integrated hearing protectors used in low-frequency-dominated noise, and with the prototype evaluations of Brammer et al. (2014) and Lee et al. (2014), who reported marked improvements in speech recognition when ANC was combined with amplification in circumaural devices.

The Gain+DNR condition also produced a statistically significant improvement over Gain Only in both groups, confirming the perceptual benefit of the envelope-preserving DNR algorithm. The algorithm, originally introduced by Poluboina et al. (2022), minimises the mean squared error between the clean and processed speech envelopes, thereby preserving the temporal envelope cues that are important for speech intelligibility, particularly in individuals with sensorineural hearing loss. Hearing-impaired individuals rely heavily on the temporal envelope for speech perception (Shannon et al., 1995); Thus, an algorithm that preserves envelope structure while suppressing noise is expected to yield perceptual benefits that more aggressive suppression approaches cannot achieve. Earlier studies have similarly demonstrated that less aggressive noise reduction produces better speech intelligibility than approaches that apply greater gain suppression (Loizou, 2007; ZhengAlnoury et al., 2021), and the present results are consistent with this evidence base.

A key difference emerged between the two participant groups in the comparison between Gain+ANC and Gain+DNR when applied independently. In the hearing-impaired group, the Gain+ANC condition produced significantly lower SRTn values compared to Gain+DNR (estimate = −2.06, $p = .014$), indicating that ANC conferred a greater individual benefit than DNR alone in this population. This may reflect the particular susceptibility of hearing-impaired listeners to low-frequency noise masking, given their reduced spectral resolution and elevated absolute thresholds, which render ANC-mediated low-frequency attenuation especially beneficial. In contrast, in the normal-hearing group, the Gain+ANC and Gain+DNR conditions did not differ significantly from each other (estimate = −1.20, $p = .375$), suggesting that both technologies contributed comparable individual benefit when applied to listeners with intact auditory function. This distinction underscores the importance of evaluating hearing protection systems separately across listener populations, as the relative contribution of individual processing components may vary depending on the underlying auditory status.

The most important finding was that the Hybrid condition (Gain+ANC+DNR) significantly outperformed all partial-component conditions in both groups, demonstrating a clear additive benefit when ANC and DNR were combined. In the hearing-impaired group, the Hybrid condition achieved an EMM of 74.1 dB SRTn, representing an improvement of 8.33 dB over Gain Only ($p < .001$), 5.08 dB over Gain+DNR ($p < .001$), and 3.02 dB over Gain+ANC ($p < .001$). In the normal-hearing group, the Hybrid condition achieved an EMM of 67.9 dB SRTn, representing an improvement of 6.24 dB over Gain Only ($p < .001$), 3.14 dB over Gain+DNR ($p < .001$), and 1.94 dB over Gain+ANC ($p = .015$). This additive advantage is mechanistically coherent: ANC reduces the noise floor entering the earcup in the low-frequency region, while the DNR algorithm suppresses residual noise components across mid-frequencies in the processed signal before amplification. The combined action of these two stages, hence, addresses noise masking across a wider frequency range than either technology alone, and this is corroborated by the insertion loss data, which confirmed that the Hybrid configuration produced the most detailed broadband attenuation profile.

5.2. Interaction of Condition and Participant Group

Both the hearing-impaired and normal-hearing groups demonstrated a consistent hierarchical pattern of performance across conditions, with Gain Only yielding the poorest and the Hybrid condition yielding the best speech-in-noise performance. The magnitude of improvement associated with the Hybrid condition relative to Gain Only was larger in the hearing-impaired group (8.33 dB SRTn) than in the normal-hearing group (6.24 dB SRTn). This differential benefit in the hearing-impaired group likely reflects their greater baseline susceptibility to noise masking attributable to sensorineural pathology. Individuals with SNHL typically exhibit reduced frequency selectivity, elevated absolute thresholds, and impaired temporal fine structure processing, all of which heighten the detrimental impact of background noise on speech recognition (Festen & Plomp, 1990). The greater absolute benefit observed in the hearing-impaired group indicates that the hybrid system is particularly well suited to the population for whom it is primarily intended.

It is also notable that the normal-hearing group demonstrated absolute SRTn values approximately 6–8 dB lower than the hearing-impaired group across corresponding conditions, reflecting the expected difference in speech-in-noise performance between these populations. The fact that the normal-hearing group also derived significant benefit from all active processing conditions despite their greater intrinsic listening capacity suggests that the hybrid system improves the listening situation for all users of the device, not only those with pre-existing auditory impairment.

5.3. Insertion Loss Characteristics and Implications for Noise Protection

The insertion loss data provided complementary evidence regarding the noise attenuation mechanisms operating under each headset configuration. The finding that passive only provides substantial mid- and high-frequency protection but limited low-frequency benefit is consistent with the established physical principles governing circumaural hearing protectors (Berglund et al., 1996; Kuo & Morgan, 1999). The observed extension of low-frequency insertion loss in the ANC Only condition confirms that the feedforward and feedback ANC architecture of the Sennheiser HD 560S headset successfully delivers additional attenuation in the spectral region where passive mechanisms are least effective.

The gain-inclusive conditions demonstrated a predictable reduction in net insertion loss at speech frequencies, directly attributable to the gain applied through the NAL-NL2 prescription stage. This apparent reduction in insertion loss does not represent a hazard to the listener; rather, it reflects the intentional restoration of speech audibility within the earcup environment. The DNR algorithm, when incorporated into the processing chain, partially counteracted the noise amplification associated with the gain stage by suppressing noise components in the processed signal, as evidenced by the modest increase in mid-frequency attenuation in the DNR + Gain condition relative to the Gain Only condition. The Hybrid System (ANC + DNR + Gain) produced the most favourable overall insertion loss profile, confirming that the simultaneous operation of passive attenuation, ANC, DNR, and gain achieves the most detailed noise reduction across the frequency range.

CHAPTER 6

SUMMARY AND CONCLUSION

The present study aimed to develop and evaluate a proof-of-concept hybrid hearing protection and communication system that integrated passive earmuff attenuation, active noise cancellation (ANC), and an envelope-preserving digital noise reduction (DNR) algorithm within a single real-time signal processing platform.

The specific objectives of the study included:

- To compare speech recognition in industrial noise across amplification-only, amplification with ANC, amplification with DNR, and amplification with combined DNR and ANC processing configurations.
- To measure and compare insertion loss across the different processing configurations using probe microphone measurements relative to the unprotected open-ear condition.

To evaluate the above objectives, speech perception in noise was measured using an adaptive staircase sentence recognition task presented in recorded industrial machinery noise, and insertion loss was assessed using probe microphone measurements across six headset configurations. A total of 37 participants were enrolled: 25 individuals with mild to moderate bilateral sensorineural hearing loss (Group I) and 12 individuals with normal hearing sensitivity (Group II).

In the hearing-impaired group, the HPD condition had a highly significant influence on speech recognition in noise. Among all conditions tested, Gain Only resulted in the poorest speech-in-noise performance, indicating that passive attenuation combined with amplification alone was insufficient to meaningfully improve the listening situation. The Hybrid condition consistently produced the best performance, demonstrating that the simultaneous integration of ANC and DNR with amplification yielded the greatest benefit. When the technologies were evaluated individually, ANC conferred a greater benefit than DNR alone in this group, suggesting that reduction of low-frequency noise at the ear canal as achieved by ANC is particularly advantageous for listeners with sensorineural hearing loss, who are especially susceptible to noise masking.

In the normal-hearing group, a similar pattern was observed, with the Gain Only condition yielding the poorest performance and the Hybrid condition yielding the best. However, a notable distinction emerged when ANC and DNR were applied independently, neither technology produced a meaningfully greater benefit than the other in normal-hearing listeners, indicating that both contributed comparably when used in isolation. Despite this, the Hybrid condition significantly outperformed both individual active conditions, confirming that the additive benefit of combining ANC and DNR was evident regardless of audiometric status. Insertion loss measurements further confirmed that the Hybrid configuration provided the most detailed noise attenuation across the frequency range in both groups, with ANC extending low-frequency protection and DNR contributing additional mid-frequency noise suppression.

To conclude, the present study demonstrated that the novel hybrid hearing protection system achieved significant improvements in speech perception in noise compared with passive protection and amplification alone, in both hearing-impaired and normal-hearing individuals. The integration of ANC and DNR within a single platform produced an additive benefit that exceeded either technology used independently. A key differential finding was that ANC conferred greater individual benefit than DNR in the hearing-impaired group, whereas both technologies performed comparably when applied in isolation in the normal-hearing group. The envelope-preserving DNR algorithm proved effective in reducing noise without compromising the temporal speech cues important for intelligibility. The insertion loss findings confirmed that the Hybrid configuration provides the broadest protective attenuation profile across the frequency range, establishing this proof-of-concept system as a promising foundation for the development of personalised, multi-technology hearing protection solutions for occupational use.

6.1. Implications of the Study

- The significant improvement in speech-in-noise performance afforded by the Hybrid system has direct implications for audiological management of workers with sensorineural hearing loss in occupational settings, where existing solutions inadequately address both noise hazard and communication need.
- The use of the NAL-NL2 prescription target within a hearing protection platform indicates that individualised audiometric data should be incorporated into the fitting of occupational hearing protection devices for workers with hearing impairment, paralleling best-practice hearing aid fitting principles.
- The findings provide direction for audiologists counselling hearing aid users in occupational environments: noise reduction and active noise cancellation do not perform equivalently across all listener populations, and combined systems offer perceptual benefits that neither component alone can reliably achieve.
- The results provide direction to hearing protection device manufacturers: integrating ANC with an envelope-preserving noise reduction algorithm into amplifying earmuffs represents a technically feasible and perceptually meaningful advancement over current commercial offerings.
- The proof-of-concept implementation using commercially available hardware (Sennheiser HD 560S and a laptop) demonstrates that effective hybrid protection is achievable without proprietary custom engineering, which has implications for accessibility and scalability in low-resource occupational settings.

6.2. Future Directions

- The signal processing chain can be miniaturised onto an embedded DSP or system-on-chip platform to produce a truly portable, wearable device suitable for deployment in authentic industrial environments.
- The system should be evaluated across a wider range of industrial noise levels (e.g., 70–100 dB[A]) and noise types (e.g., impulsive, mixed-source) to establish the generalisability of the perceptual and attenuation benefits.
- Multi-microphone beamforming can be integrated with the envelope-preserving DNR algorithm to provide additional directional benefit and further SNR improvement beyond what the current single-channel implementation achieves.
- Future studies should incorporate subjective outcome measures, including listening effort, user comfort, and situational awareness ratings, to comprehensively characterise the real-world benefit and user acceptance of the hybrid system.
- The DNR algorithm can be integrated with deep learning-based speech enhancement models to further improve performance in highly non-stationary noise environments.
- A dynamic, frame-by-frame noise estimation approach can be applied to enable real-time adaptive switching of the DNR gain function in response to rapid changes in the acoustic environment.
- Longitudinal field trials in authentic occupational settings are required to evaluate the effectiveness, safety, and user compliance of the hybrid system over extended periods of use.

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