EFFECT OF HEARING AID USE ON SPATIAL RELEASE FROM MASKING IN INDIVIDUALS WITH SINGLE-SIDED DEAFNESS

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CERTIFICATE

This is to certify that this dissertation entitled **"Effect of Hearing Aid Use on Spatial Release from Masking in Individuals with Single-Sided Deafness"** isabonafideworksubmittedaspartof the fulfillmentof the degree of Master of Science **(Audiology)** of the student with Registration Number **P01II24S023009**. 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 ofany other Diploma or Degree.

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8 June, 2026

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CERTIFICATE

This is to certify that this dissertation, entitled "**Effect of Hearing Aid Use on Spatial Release from Masking in Individuals with Single-Sided Deafness**", 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 **"Effect of Hearing Aid Use on Spatial Release from Masking in Individuals with Single-Sided Deafness"** is the result of my own study under the guidance of **Dr. Sahana P., Assistant Professor of Audiology**, C-PEC, Centre of Excellence, All India Institute of Speech and Hearing, Mysuru and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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Chapter 1

Introduction

Single sided deafness (SSD) refers to a severe or profound sensorineural hearing loss in one of the ear with normal or near normal hearing in the other ear (Pantaleo et al., 2024; Sahoo et al., 2025). Adult onset single sided deafness can occur instantaneously, as seen in idiopathic sudden sensorineural hearing loss, or it can advance to a secondary consequence of underlying issues like chronic ear infections, acoustic neuromas, meningitis, Meniere's disease or physical trauma to the ear (Pantaleo et al.,2024; Peter et al., 2019a).

Individuals with SSD are fundamentally deprived of the physiological advantages such as natural binaural auditory processing; consequently, they exhibit profound deficits in spatial sound localization and experience severely degraded speech intelligibility in complex, noisy environments due to the absence of dependable interaural time differences (ITDs) and interaural level differences (ILDs) (Pantaleo et al., 2024; Sladen, 2021). To fully apprehend the depth of this impairment, it is necessary to elucidate the core mechanisms of binaural integration that operate within a healthy central auditory nervous system (CANS): specifically, the binaural squelch mechanism, binaural summation, and the acoustic head shadow effect (Carhart, 1965).

Binaural summation is a neurophysiological phenomenon wherein the central auditory system integrates identical acoustic stimuli arriving at both cochleae, resulting in a perceived signal enhancement. For an individual with normal bilateral hearing, a sound presented to both ears is perceived as approximately 3 to 6 decibels (dB) louder and significantly more robust than the identical acoustic stimulus presented monaurally (Litovsky, 2012). This summation provides a redundant neural representation of the auditory environment, thereby lowering the absolute threshold of hearing and reducing the cognitive listening effort required to achieve baseline audibility. In patients with SSD, this fundamental advantage is entirely obliterated, forcing the brain to operate on a biologically impoverished, monaural signal stream.

Concurrently, the binaural squelch mechanism operates as the brain’s intrinsic, highly sophisticated noise-reduction algorithm. When a target speech signal and competing background noise originate from distinct spatial locations, the acoustic signals reaching each ear differ infinitesimally in their time of arrival (ITDs) and their intensity (ILDs) (Carhart, 1965). The central auditory system—specifically at the level of the medial superior olive (MSO), which computes low-frequency ITDs, and the lateral superior olive (LSO), which computes high-frequency ILDs—compares these interaural phase and amplitude disparities.

By processing these differences, the brain is able to "squelch" or actively suppress the competing background noise, filtering it out of the perceptual foreground (Vannson et al., 2020). This central unmasking allows the higher auditory cortices to focus exclusively on the target speech, significantly improving the functional signal-to-noise ratio (SNR). Because the squelch effect relies entirely on the precise temporal and spectral integration of inputs from two functioning ears, SSD patients are entirely stripped of this central filtering capability.

Finally, the "head-shadow" effect dampens high-frequency sounds arriving from the poorer side because the physical mass of the skull acts as an acoustic barrier, further impairing speech intelligibility and spatial awareness (Pantaleo et al., 2024).

The downstream consequences of this unilateral sensory loss extend far beyond simple auditory attenuation, triggering a cascade of psychosocial and cognitive disruptions that severely compromise an individual's daily functioning and quality of life. In dynamic, multitalker environments—such as open-plan offices, busy restaurants, classrooms, or public transportation—the inability to segregate target speech from competing babble leads to immediate and catastrophic communication breakdowns. Without the noise-suppressing benefits of binaural squelch, the brain is bombarded by an unsegregated mass of acoustic data. Recent studies utilizing the National Acoustic Laboratories Dynamic Conversation Test (NAL-DCT) and the Speech, Spatial, and Qualities of Hearing Scale (SSQ12) have demonstrated that individuals with UHL exhibit significantly longer reaction times during speech-in-noise comprehension tasks, indicating a massive surge in cognitive load and listening effort compared to normal-hearing cohorts.

To compensate for this lack of spatial orientation, patients often exhibit exaggerated head movement tracking, attempting to manually orient their better ear toward the acoustic target, which further adds to physical and cognitive fatigue. The relentless cognitive exertion required to participate in basic multitalker conversations frequently culminates in profound communicative fatigue. Consequently, patients routinely develop avoidance behaviours. Data from the Social Participation Restrictions Questionnaire (SPaRQ) confirms that untreated SSD leads directly to social withdrawal; patients begin declining social invitations, avoiding group settings, or adopting the unhelpful coping mechanism of "tuning out" and remaining entirely silent during conversations to mask their deficit (Bennett et al., 2021,).

The secondary consequence of social isolation deeply affects mental health and interpersonal relationships. As the daily communication becomes increasingly effortful and less spontaneous, it is a huge burden on the normal-hearing partner who is frequently forced to take the role of a social gathering interpreter. This leads to misunderstandings, frustration, annoyance anger and hostility (Kleckner Audiology, 2024). The psychological toll extends far beyond relationship struggles. Without intervention, patients with SSD have a significantly higher risk of developing anxiety in social situations, withdrawal due to severe depression, decreased self-esteem, and feelings of embarrassment (Kleckner Audiology, 2024; Bennett et al., 2021). Ultimately, these affected individuals tend to have noticeable decline in quality of life & frustration because of prolonged fatigue during communication. (Pantaleo et al., 2024; Peter et al., 2019a).

To understand how the auditory system detects sources in the noisy environments, one must look to the spatial release from masking (SRM). Clinically, it is defined as the measurable improvement in speech intelligibility when the target speech and competing noise come from different spatial locations rather than the collocated. In other words, when there is a spatial separation, it allows listeners with normal binaural hearing to naturally unmask the speech signal with the help of interaural cues and head-shadow effect. For individuals with normal hearing, shifting the noise source away from the speech axis results in a robust spatial release from masking, often improving the signal-to-noise ratio by several decibels.

This robust spatial release from masking is not a static physiological constant; rather, its magnitude is characterized by significant variability dependent on several interacting environmental and acoustic parameters. Foremost among these is the azimuth, the specific spatial separation between the target signal and the competing noise, the masker type, and the degree of reverberation in the acoustic environment (Litovsky, 2005).

There are several variables that can affect spatial release of masking. Shifting the noise source from 0° to ±45° or ±90° alters the ITD and ILD reaching the auditory system. SRM reaches its peak at ±90°, where there is absence of monaural cues that forces the auditory system to depend entirely on binaural unmasking to isolate auditory streams (Misurelli and Litovsky, 2012). Energetic maskers (e.g., white noise) interfere at the cochlear level, while informational maskers (e.g., multi-talker babble) cause cognitive and semantic interference at the higher auditory system. SRM yields a larger dB improvement against informational maskers. Competing or multiple voices with same-gender allow most spatial separation; however different-gender voices are somewhat unmasked because of the pitch differences alone (Bernstein et al., 2015). Room reflections act as a noise and fill the time-based dips in masking noise and smear ITD fine-structure cues, considerably degrading SRM. In a speech recognition task against multitalker noise, moderate reverberation elevated SRTs and reduced SRM by an average of 5.4 dB when compared to an anechoic setting (Momtaz et al., 2025).

Before exploring the various clinical rehabilitation modalities, it is critical to acknowledge the profound neurobiological and structural alterations triggered by unilateral auditory deprivation (UAD) within the central auditory pathways. The sudden or congenital loss of input from one ear does not leave the auditory cortex in a state of dormant waiting; instead, it initiates rapid, bidirectional cross-modal and intra-modal reorganisation (Kral et al., 2013). In a healthy system, unilateral acoustic stimulation evokes predominantly contralateral activation in the auditory cortex. However, the disruption of binaural inputs in SSD results in an "auditory preference syndrome." Functional magnetic resonance imaging (fMRI) reveals a marked neuroplastic weakening in the cortical representation of the deprived ear, accompanied by a maladaptive strengthening in the representation of the intact ear (Vannson et al., 2020). While this reorganization is theoretically adaptive for monaural listening—allocating more cortical resources to the better ear—it becomes highly disadvantageous if hearing is later restored to the poorer ear, as the brain has effectively down regulated its capacity to process input from that side.

Furthermore, sensory deprivation in SSD is not merely a loss of absolute volume; it results in measurable spatiotemporal neuronal delays. Advanced magnetoencephalography (MEG) studies on human lifespan cohorts have discovered cumulative delays in the auditory evoked magnetic fields (AEF) to tones, indicating that the neural processing of interaural phase changes slows down significantly as auditory deprivation persists, a phenomenon not seen in constant visual delays (Tiitinen et al., 1999). To map the precise etiology of this deficit, developmental models utilizing guinea pigs have been employed. By inducing unilateral conductive hearing loss during early critical periods, researchers observed profound structural alterations and a prolonged maturation of the binaural auditory brainstem (Anbuhl et al., 2025). Single-unit recordings of auditory midbrain neurons in these animal models revealed a severe degradation in neural acuity, specifically for high-frequency sound location cues. Because the precise, sub-millisecond timing required for decoding interaural timing differences relies heavily on structurally pristine inhibitory synapses in the central auditory pathway, prolonged sensory deprivation causes aberrant synaptic functioning (Kral et al., 2013). Consequently, patients experience severe adaptation issues where the central nervous system can no longer accurately compute temporal disparities, fundamentally impeding the potential efficacy of delayed cochlear implantation or amplification.

Several rehabilitation options are available for patients with Single-Sided Deafness (SSD). Contralateral routing of signal (CROS) hearing aids and bone conduction devices (BAHA or other bone-anchored implants) work by redirecting sounds from the poorer ear to the better ear (Snapp et al., 2017a). CROS systems consist of a microphone capturing acoustic input from the poorer side and wirelessly streaming that acoustic information across the head to a receiver in the better ear, while bone conduction devices capture sound on the poorer ear side and transmit it through skull vibrations to the cochlea of the contralateral hearing ear (Peters et al., 2015a). These rerouting devices serve to alleviate the head-shadow effect (Pantaleo et al., 2024). Another option is a cochlear implant (CI) in the poorer ear, which is an electronic device with an electrode array that directly stimulates the auditory nerve (Arndt et al., 2011). Current practice guidelines permit CI in patients with SSD if the poorer ear has profound loss and the other ear is normal (Grossmann et al., 2016a).

In quiet listening conditions, since background noise is absent, adults with SSD often manage fairly well on a day-to-day basis. While it may appear that individuals manage adequately in these optimal settings, traditional audiological assessments conducted in quiet—such as pure-tone audiometry (PTA) and word-recognition in quiet (WRQ)—are notoriously plagued by a pervasive ceiling effect (Litovsky et al., 2006). Why is SRM testing vastly more sensitive and clinically relevant than quiet testing? The primary reason lies in the inability of quiet testing to capture the true ecological validity of real-world auditory demands. When an SSD patient is assessed in a sound-treated clinical booth without competing noise, the normal-hearing contralateral ear is fully capable of processing the target speech without any semantic interference. Consequently, patients frequently score between 95% and 100% on speech perception in quiet, regardless of the rehabilitation device utilized (e.g., CI, CROS, or unaided) (Massa and Ruckenstein, 2014). This severe ceiling effect masks the profound, underlying deficits the patient experiences in their daily life, rendering the test effectively blind to true Listening Difficulties (LiD) (Zadeh et al., 2024). Daily auditory reality is not a series of isolated spondee words presented in a silent room; it is a highly dynamic, spatially complex environment fraught with competing signals that demands the parsing of emotional cues, inflections, and spatially separated voices (Litovsky, 2012).

Because spatial release from masking forces the central auditory system to rely on binaural integration (specifically ITDs and ILDs) to separate a 0° azimuth target from ±90° azimuth maskers, it directly taxes the neural pathways that SSD destroys. Furthermore, SRM testing allows for the objective quantification of cognitive fatigue, an metric completely ignored by quiet testing. Recent studies employing advanced pupillometry have demonstrated that spatial separation of target and masker speech not only improves speech intelligibility but also facilitates a "spatial release from listening effort" (SRE) (Oh et al., 2023,).

Peak proportional pupil dilation (PPD), a highly sensitive autonomic biomarker for cognitive exertion, reveals that while an SSD patient might achieve functional comprehension in a co-located noise environment, they do so at a massive, unsustainable cognitive cost. SRM testing captures this nuance, proving that restoring binaural cues reduces the raw physiological effort required to listen. It is for this exact reason that the FDA and modern clinical guidelines have shifted away from evaluating implant efficacy using quiet metrics like the HINT (Hearing in Noise Test administered without spatial separation), acknowledging that a more demanding, spatially separated test is strictly required to bypass the ceiling effect and accurately index device performance (Goupell et al., 2016).

Nevertheless, rehabilitation devices can improve awareness of sounds originating towards the poorer ear. CROS and BAHA systems bring quiet signals from the disabled side into the better ear, raising audibility (Snapp et al., 2017a). Cochlear implantation grants the SSD patient a second functioning ear, providing bilateral stimulation even in quiet (Arndt et al., 2011). However, the extreme benefits occur in complex environments. Most studies emphasize that the key advantages of SSD treatments manifest in noisy situations rather than in silence (Peters et al., 2015a). For cochlear implants, providing a CI to the poorer ear restores spatial hearing benefits. Grossmann et al. (2016) showed that adults with SSD who were implanted with a CI performed significantly better on speech-in-noise tests when the target and noise were spatially separated. In the same way, a Swiss multicentre trial found that CI users with SSD experienced true spatial release when the target and masker noise originated from opposing directions (Peter et al., 2019a).

Multiple researches have analyzed the impact of these interventions on spatial release of masking in SSD. With reference to cochlear implants, evidence confirms that stimulating the poorer ear re-establishes spatial hearing advantages. Grossmann et al. (2016b) and Oh et al. (2023) demonstrated that adults with SSD using a CI achieved significantly higher speech-in-noise scores in spatially separated target-masker conditions. These researchers observed sizable improvements in the implanted state compared to unaided listening when noise was separated at a distance from the speech source. In essence, spatial release from masking can be restored in patients with SSD using a cochlear implant (Grossmann et al., 2016b; Oh et al., 2023). Likewise, Peters et al. (2019b) in a Swiss multicentre study noted a 3 dB SRM improvement when stimuli were opposed. This demonstrates that CI recipients successfully harness binaural cues for enhanced auditory processing in noise (Peter et al., 2019b).

On the other hand, rerouting technologies are unable to restore binaural processing, thus they inherently cannot facilitate genuine spatial release. CROS and BAHA options simply transfer acoustic inputs from the poorer side to the better ear; they alleviate the head shadow but cannot provide reverse head-shadow benefits nor permit interaural comparisons (Peter et al., 2019b; Snapp et al., 2017b). Literature highlights that CROS and BAHA provide marginal or unreliable performance in noise. Conventional CROS and bone-anchored devices usually yield contradictory findings with minor effects on speech understanding in noise (Peters et al., 2015b). Moreover, recent Indian audiological research by Sahoo et al. (2025) discovered that patients chose CROS primarily for convenience. Although users conveyed these rerouting hearing instruments assisted in sound awareness towards the poorer ear, they were definitively unsuccessful in enhancing localization abilities or spatial release.

Consequently, spatial release of masking remains fundamentally absent for CROS/BAHA users due to the complete physiological absence of reliable binaural cues required for processing background noise environments and spatially separated complex signals.

When assessing these options, it is essential to consider the benefits and drawbacks of each configuration, grouping their individual strengths and weaknesses. The primary advantages of CROS, BiCROS, and conventional Behind-The-Ear (BTE) hearing aids revolve around their non-invasive nature, accessibility, and high cost-effectiveness (Deepthi et al., 2021). They offer immediate audiological support without requiring medical approval. The advantages of BAHA and CI include direct stimulation of the cochlea or auditory nerve, which restores binaural input for the patient that can yield robust sound awareness (Arndt et al., 2011). Despite these advantages, devices also present notable drawbacks. Both cochlear implants and some bone-anchored hearing devices necessitate invasive surgical intervention, inherently exposing the patient to substantial clinical risks. These include increased intraoperative bleeding, general postoperative complications, and the potential for hardware extrusion (Peter et al., 2019a). The disadvantages of CROS and BiCROS include a dependence on the better ear's processing, previously assumed to yield inconsistent gains in noise.

Despite historical perspectives, recent audiological revisions highlight the evolving role of conventional amplification. While CROS and BAHA systems overcome the head-shadow effect by bringing sound to the better ear, emerging evidence suggests optimised traditional BTE configurations offer evident advantages (Wagener et al., 2018a). When the better ear also has hearing loss, hearing aids for SSD are often modified, typically utilising a BiCROS setup (Snapp et al., 2017a). Still, advanced digital signal processing in modern BTEs is shifting this paradigm. By utilising sophisticated directional microphones and advanced noise-reduction algorithms, conventional BTEs pointedly improve the overall signal-to-noise ratio. Subsequently, patients fitted with high-tier conventional BTEs demonstrate a renewed capacity for spatial release of masking.

Compared to other rehabilitative devices, why do modern BTE hearing aids offer a better advantage for SSD patients in helping spatial release from masking? The answer relies on the fundamental fact that conventional hearing aids differ in acoustic amplification when compared to electrical stimulation by a cochlear implant, which lacks naturalness. Cochlear implant processors and their coding strategies often degrade temporal fine structure (TFS) information (Fischer et al., 2021). CIs divide the signal into band pass filters and use only the envelope to generate a high-rate pulse train. When the temporal fine structure (TFS) is severely degraded, it compromises the perception of interaural time differences. Without access to these critical low-frequency phase delays, the auditory system is left unable to reliably localise sound horizontally or utilise binaural squelch to filter out background noise (ITDs)(Fischer et al., 2021; King et al., 2017).

On the other hand, when a single-sided deaf patient retains residual low-frequency hearing in the affected ear, fitting a high-power conventional BTE preserves both the envelope and fine-structure cues (Gifford et al., 2015). It is known that envelope and temporal fine structure cues go hand in hand. While fine structure is dominant for pitch perception, and based on ITD, minute differences can be detected in complex maskers, the dependence on the time-based cues increases dynamically as outer hair cells are almost damaged and frequency information is hampered (Hearing Review, 2024). When programmed appropriately for the individuals, BTE can help in extracting these low-frequency cues and combine them with the contralateral input from the better ear to restore binaural processing (Gifford et al., 2015). Moreover, the location of BTE microphones above the pinna gives better output for sounds arriving from ±90° azimuth. Ultimately, this improves the head shadow benefit and the access to ILDs, especially for the population with SSD (D'Onofrio et al., 2020). When these informations are better represented through the conventional BTE device, it allows users to better separate out speech from background noise, and consequently, improve the spatial release of masking can certainly be facilitated by it. (Wagener et al., 2018b). Finally, for many patients who are in search of cost-effective and non-invasive audiological intervention, the most practical and accessible solution for achieving spatial release of masking is the conventional BTE.

Need for the study

Single sided deafness poses significant auditory, cognitive and psychological challenges that greatly impacts quality of life. Patient's affected with SSD struggle ith sound localisation, speech perception in noise, and increased listening effort, leading to communication breakdowns in everyday settings such as workplaces, social gatherings, or noisy public spaces (Vincent et al., 2015; Firszt et al., 2017; Wie et al., 2010). These overwhelming deficits result increased cognitive load, social withdrawal, and reduced work performance, which gives rise to long term anxiety and diminished well-being as a consequence (Lucas et al., 2018; Liu et al., 2018; Tyler & Baker, 1983).

With over 63 million people affected because of hearing loss, India has prevalence of 7.9%-13.3% with unilateral sensorineural hearing loss. Among these affected people, SSD specifically is reported to be 1.9% among 11,534 sensorineural hearing loss cases (Varshney, 2016; Singh et al., 2021; Chowhan, 2018). In a country like India which has diverse linguistic and cultural landscape, this high prevalence requires the urgent need for structured interventions that address the challenges faced by adults with SSD.

Spatial release from masking (SRM) is one of the main auditory mechanisms used by normal individuals to make use of binaural cues (interaural time and level differences) to improve speech intelligibility by 10-15 dB in noisy environments (Litovsky, 2012). Absence of binaural inputs severely impairs SRM. Hence in SSD individuals it is difficult for them to segregate the speech from noise in day to day life situations such as crowded markets or multilingual settings that are common in India (Asp & Reinfeldt, 2019).

Current interventions, such as bone-anchored hearing aids (BAHA), contralateral routing of signals (CROS), and cochlear implants (CI), have limitations. BAHAs and CIs are invasive and costly, often inaccessible in resource-constrained settings, while CROS systems provide inconsistent SRM benefits, particularly in adults, and may compromise sound quality or localisation (Snapp et al., 2017; Marx et al., 2019; Fogels et al., 2020). In India, where healthcare affordability and accessibility are critical barriers, these solutions are often impractical for widespread adoption (Jain et al., 2023).

Conventional high-power hearing aids fitted to the poorer ear represent a non-invasive, cost-effective alternative to make use of residual hearing that remains underexplored for SRM in SSD. While studies like Devi et al. (2015, 2017) have shown superior speech-in-noise performance for digital BAHAs over CROS in Indian adults and children, few investigations have systematically evaluated SRM with modern air-conduction hearing aids equipped with advanced features like feedback cancellation and frequency lowering (Asp & Reinfeldt, 2019; Bishop et al., 2017). Moreover, there is a paucity of within-subject studies comparing aided and unaided SRM across spatial configurations (S0N0, S0NB, S0NP) in SSD populations, particularly in non-Western contexts where linguistic diversity (e.g., Kannada as a native language) and environmental noise profiles may influence outcomes (Singh et al., 2021; Jain et al., 2023). This gap is critical, as cultural and linguistic factors, such as the tonal and syllabic structure of Kannada, may affect speech perception and the efficacy of hearing aid amplification in noisy settings.

The need for this study is further amplified by the broader implications of untreated SSD. Beyond auditory deficits, SSD is linked to cognitive decline due to increased listening effort, which may exacerbate age-related cognitive impairments in adults (Lin et al., 2013). In India, where social interactions are often multilingual and occur in high-noise environments (e.g., urban markets, public transport), effective SRM could significantly enhance communication and social participation. By evaluating SRM with conventional hearing aids, this study aims to provide evidence for a scalable, affordable intervention that could reduce the burden on patients and healthcare systems. Such findings could inform clinical guidelines, support personalised rehabilitation strategies, and advocate for policy changes to improve access to hearing aids in India’s public health framework.

This study addresses a critical research gap by:

- Investigating SRM in Indian adults with SSD using Kannada stimuli, accounting for linguistic and cultural specificity.

- Providing within-subject comparisons of aided vs. unaided SRM across ecologically relevant spatial configurations.
- Exploring the potential of modern conventional hearing aids as a viable alternative to invasive or costly devices to make use of residual hearing, aligning with India's need for accessible healthcare solutions.

Moreover, the audiological outcomes derived from this study will offer valuable insights into the efficacy of hearing aid amplification for SSD. Specifically, it will quantify improvements in speech identification scores (SIS) across spatial conditions, revealing the extent of SRM benefits (e.g., SRM_B and SRM_P) in aided versus unaided scenarios, potentially demonstrating up to several dB gains when noise is directed toward the poorer ear due to restored head-shadow effects (Asp & Reinfeldt, 2019).

These outcomes could elucidate the role of partial binaural cues, such as interaural level differences (ILDs), in enhancing binaural squelch and summation, thereby reducing listening effort and auditory fatigue.

Additionally, the results may validate optimised hearing aid programming protocols (e.g., using NAL-NL2 with omnidirectional microphones and enabled noise reduction) for SSD, providing evidence-based recommendations for audiologists to maximise audibility in the poorer ear without distorting spatial cues.

Ultimately, these audiological metrics could guide device selection, fine-tune fittings for better speech-in-noise performance, and contribute to standardised assessment tools for SSD rehabilitation in diverse populations. The outcomes could transform clinical practice by offering evidence-based recommendations for hearing aid use in SSD, ultimately improving communication, reducing cognitive load, and enhancing quality of life for millions of affected individuals in India and beyond.

Aim of the study

The study was to investigate the amount of spatial release of masking with and without a digital BTE hearing aid in individuals with single-sided deafness.

Objectives of the study

The objectives of the study were

Objective 1

To quantify speech identification scores (SIS) in individuals with single-sided deafness (SSD) under unaided and aided listening conditions across three spatial configurations:

a. Speech and noise co-located at 0° azimuth (S0N0).
b. Speech at 0° azimuth with noise directed toward the better ear (S0NB).
c. Speech at 0° azimuth with noise directed toward the poorer ear (S0NP).

Objective 2

To calculate and compare spatial release from masking (SRM) between unaided and aided listening conditions:

a. SRM toward the better ear (SRM_B = SIS in S0NB − SIS in S0N0)
b. SRM toward the poorer ear (SRM_P = SIS in S0NP − SIS in S0N0)

Chapter 2

Review of literature

Binaural hearing provides several key advantages that enhance auditory processing in everyday environments. One such advantage is the head-shadow effect occurs when the head attenuates high frequency sounds arriving from one side, reducing their intensity at the opposite ear and aiding in signal detection from the better-hearing side (Dillon, 2001; Schleich et al., 2004). Next, binaural summation allows sounds to be perceived as louder when processed by both ears, improving overall sensitivity (Dillon, 2001; Schleich et al., 2004). Further, binaural squelch refers to the central nervous system's ability to suppress background noise and enhance focus on a target signal through interaural comparisons (Dillon, 2001; Schleich et al., 2004). All these mechanisms rely on interaural time differences (ITDs) and interaural level differences (ILDs), which are critical for sound localisation (Blauert, 1997; Klumpp & Eady, 1956; Mills, 1960). The absence of input from either of the ears may disrupt these binaural processes, leading to significant auditory challenges and difficulties in sound localisation due to the loss of ITDs and ILDs (Firszt et al., 2017; Vincent et al., 2015; Wie et al., 2010).

Single-Sided Deafness

Single-sided deafness (SSD) is defined as severe-to-profound sensorineural hearing loss in one ear with normal or near-normal hearing in the other ear (Katiri et al., 2023a; Pantaleo et al., 2024a). In SSD, the ‘good’ ear typically has pure-tone thresholds around 30 dB HL or better, while the poorer ear has minimal or no useful hearing (Baguley et al., 2006; Vincent et al., 2015).

Etiology

Possible aetiologies that can cause SSD are inner ear infections such as mumps and cytomegalovirus (CMV), metabolic/circulatory diseases, Ménière’s disease, head trauma, genetic, vestibular schwannoma/ acoustic neuromas, inner ear malformations, cochlear nerve defects, auditory neuropathy spectrum disease, ototoxicity, otosclerosis, & chronic otitis media with and without cholesteatoma. It can also be idiopathic (Chowhan, 2018; Pantaleo et al., 2024; Penwal et al., 2024; Schreiber et al., 2010; Swain, 2024). Tinnitus would co-occur with unilateral hearing loss (reported in 80% of cases) and an overall reduction in quality of life due to the loss of the auditory field on one side. (Katiri et al., 2023b; Pantaleo et al., 2024b)

Clinical Presentation

Patients with SSD have unilateral hearing loss and can hear from the other ear (Swain, 2024b). Individuals with single-sided deafness face various difficulties in daily life, especially in noisy surroundings. These issues include locating the sound source, which demands binaural hearing, grasping speech and word discrimination (Bess & Tharpe, 1986a; Swain et al., 2018). Tinnitus is one of the most common complaints among these patients, which affects not only hearing & speech understanding; it also affects the quality of life of that patient, particularly in social interaction and communication (Peters et al., 2016; Swain et al., 2018; Swain, 2024b). Vertigo is also one such symptom that affects these patients' daily living (Swain et al., 2018). Individuals with SSD may develop negative emotions, which may affect their family relationships, usually known as third-party disability (Távora-Vieira & Wedekind, 2022). If SSD is caused at a very young age, especially in children, it can have adverse effects on identifying the sound source in crowded and multi-sound source environments. Their auditory perception & speech intelligibility are hampered, which mostly reflects in their academic skills (Bess & Tharpe, 1986a; Paul et al., 2017; Peters et al., 2016).

The fundamental deficit in single-sided deafness (SSD) is the inability to leverage binaural cues. Humans utilise both ears to integrate sound signals centrally, allowing for the perception of spatial orientation and the isolation of speech from noise. The following discussion outlines the diverse psychoacoustic phenomena associated with single-sided deafness and describes how these deficits affect the listener's daily experience.

The Head Shadow Effect

The human head acts as an acoustic barrier for sounds that originate from one side of the ear to the other ear, hence it acts as an acoustic baffle. This causes a marked attenuation of the acoustic signal, specifically dampening high frequencies by the time they cross over to the contralateral ear, and this phenomenon is often referred to as the head shadow effect (Bakal et al., 2021; Tillman et al., 1963). Research indicates that the head can attenuate sounds by 3 to 10 dB, making speech directed to the poorer ear challenging to recognise without an increase in intensity (Alessandro et al., 2015).

High-frequency sounds generally cannot bend around the head, and when sound originates towards the poorer ear, the head blocks high-frequency speech cues (consonants like /s/, /f/, /t/) from reaching the better ear. In single-sided deafness, the head shadow effect yields mixed acoustic outcomes. It effectively blocks some noise from reaching the better ear, but this same acoustic barrier becomes a major burden when the listener needs to hear a signal presented to the poorer ear (Tillman et al., 1963).

This monaural, auditory phenomenon creates an interaural level difference (ILD) that improves the SNR for the ear nearest to the target signal by attenuating or dampening masker noise arriving at the ear farthest from the masker (Avan et al., 2015; Bronkhorst & Plomp, 1989). The head shadow can add up to 6 dB SNR benefit at high frequencies because attenuation is frequency-dependent and is maximised after 1.5 kHz due to the acoustic dimensions of the head (Garadat et al., 2009). When speech is directed at the poorer ear, speech intelligibility drops dramatically; this, in turn, muffles speech clarity (Heyning et al., 2016). The patient must continuously orient their better ear to position & hear favourable sounds, compelling the patient to frequently turn their head towards the source. It is documented that single-sided deafness patients develop compensatory strategies such as head-turning behaviours, but these strategies are not enough to overcome speech perception deficits in complex and dynamic environments. As the signal must "cross" the head while being masked by the noise already present at the functional ear, this effect is most disadvantageous when the signal of interest is towards the poorer ear and noise is towards the better ear.

Binaural Summation

Binaural Summation is nothing but the ability of the auditory system to integrate redundant information from both ears. It is a phenomenon where the bilateral (involvement of two ears) threshold is better than the unilateral (involvement of only one ear) threshold. If the same acoustic signal is presented binaurally, the central auditory system sums the inputs that are presented to both ears, thus enhancing central signal averaging, lowering detection thresholds, & during phonemic processing, it aids in signal detection and error correction (Cueille & Lavandier, 2025; Epstein & Florentine, 2012; Peng & Litovsky, 2021). Among normal-hearing individuals, it can be estimated that binaural summation usually provides an advantage of approximately 1–3 dB, thereby reducing the threshold, and up to a 6 dB improvement is perceived in loudness at suprathreshold levels because of the availability of redundant speech information (Peter et al., 2019; “Treatment of Single Sided Deafness,” n.d.).

However, this mechanism is totally absent in SSD due to their single functioning cochlea, and patients can effectively hear from one ear. The redundancy benefit of binaural listening is eradicated, depriving the listener of bilateral auditory integration, that is, the gain of around 2–3 dB is lost (Avan et al., 2015), which results in the loss of a 3–6 dB advantage (Rothpletz et al., 2012). Similarly, in their study, Hawkins & Wightman (1980) established that binaural advantage is eliminated in single-sided deafness patients, leading to a loss of binaural summation and reduced ease of listening (Bronkhorst & Plomp, 1989). SSD patients require signals to be physically louder to match the same sensation level as a binaural listener due to the lack of binaural summation. But even after presenting louder auditory signals, SSD patients experience reduced overall perceived loudness and clarity (Peter et al., 2019). Weak binaural summation effect increases the mean speech reception threshold (SRT) by 5–10 dB in noise compared to bilaterally hearing individuals (Timberlake et al., 2019). Additionally, when speech is directed toward the poorer ear, the head shadow effect can actually create a binaural deficit as demonstrated by Tillman et al. (1963).

Binaural squelch

Binaural squelch (BS), or the ‘cocktail party effect’, refers to the central auditory system's ability to use information from both ears to suppress background noise and improve speech understanding. Koenig, (1950) first described this sophisticated, centrally mediated neural process (central unmasking using interaural differences) in which the auditory brainstem—particularly the superior olivary complex: medial and lateral superior olives (MSO/LSO)—depend on the neural comparison of signals reaching from both ears, comparing ITDs, phase, and ILDs to decode the target signal (Pantaleo et al., 2024b). Even if the signal is heavily masked by noise at one ear, the auditory cortex can use the timing information from that noisy ear to suppress the noise component in the overall complex acoustic signal in the sound field, allowing the listener to ‘squelch’ the background noise. This depends critically on the presence of temporal fine structure (TFS) cues, particularly for low-frequency stimuli below 1.5 kHz (Litovsky, 2012). For a normal listener, as the auditory system is intact, effective separation happens between the target talker and the competing noise source, delivering approximately 2-4 dB of SNR advantage (Avan et al., 2015; Van Hoesel & Tyler, 2003). Because there is no auditory input that could be transferred by the poorer ear to provide a comparator signal, the central auditory system cannot compare interaural signals to carry out this noise subtraction. Therefore, the binaural squelch effect entirely depends upon this inter-ear comparison, which is completely absent in single-sided deafness (Avan et al., 2015).

Heyning et al. (2008) and Dwyer et al. (2014) confirmed that SSD patients lose this 2-3 dB improvement entirely in binaural processing. The most reported complaint is the inability to understand speech in background noise, as patients are unable to segregate speech from noise (Bronkhorst & Plomp, 1989). Lack of this ability leads to a major decline in speech intelligibility in reverberant, diffuse noise environments (like a cocktail party), causing SSD patients to struggle extremely compared to normal listeners, even if the signal-to-noise ratio (SNR) at their better ear is increased (Swain, 2024c). Research shows that this difficulty persists even when the noise source is presented towards the poorer ear (Vannson et al., 2015), leading to an SNR shortage of approximately 3-6 dB compared to normal listeners (Snapp, 2019). SSD individuals need at least 2-9 dB SNR higher than that of normal-hearing peers to achieve equivalent speech recognition (Katiri et al., 2023c). In summary, SSD listeners suffer in noisy, multi-source environments as they cannot use binaural squelch (Jeppsen & McMurray, 2025; Sahoo et al., 2025).

Speech In Noise

Speech-in-noise (SIN) difficulty is the most commonly reported complaint among patients with SSD. Patients consistently describe trouble following conversations in busy and noisy environments such as classrooms, meetings, restaurants, and social gatherings (Griffin et al., 2019; Welsh et al., 2004). Failure to use cues because of the head shadow effect results in a noteworthy degradation of SNR when noise arrives from the better hearing ear. Patients commonly complain, “I hear, but I don’t understand,” with unequal difficulty in different listening situations where noise is prominent (Firszt et al., 2017). Speech recognition worsens evidently when speech is directed to the poorer side and noise to the normal or near normal ear (Kitterick et al., 2016). Self-report questionnaires (e.g., SSQ) constantly show lower ratings for speech in noise and spatial hearing domains in SSD patients compared to normal-hearing controls (Shapiro et al., 2025). Clinical characteristics of these patients are that their performance strongly depends on the spatial setup, not just the overall noise level (Kitterick et al., 2016). Patients lack binaural squelch, which leads to an SNR deficit of around 3-6 dB compared to normal individuals (Snapp et al., 2017).

Research shows that this difficulty persists even when the noise source is presented towards the poorer ear (Vannson et al., 2015). Firszt et al. (2012) utilised AzBio sentence lists and showed that SSD individuals showed a 15-30% reduction in sentence recognition scores in the presence of noise, although there was increased variability in the performance across individuals. The difficulty further increased with low-context sentences. Rothpletz et al. (2012) in their study used NU-6 words in multi-talker babble & found that SSD patients required 8-12 dB more SNR to perform near to normal-hearing controls.

Cognitive Load & Listening Effort: The Neural Cost

An expanding area of research focus in the field of audiology is the cognitive load & listening effort in individuals with single-sided deafness. As a consequence of the brain's inability to automatically perform binaural processing, auditory fatigue and listening effort considerably increase. The brain must apply compensatory effort to follow conversations, an effort that is fundamentally dependent on executive functions such as selective attention and working memory (Jeppsen & McMurray, 2025; Pai et al., 2012). Increased cognitive load arises because of processing degraded monaural input, as the unaffected ear has to carry out all the auditory processing for both ears (Srinivasan et al., 2024). The degraded auditory input necessitates increased cognitive load for speech processing, raised listening effort inherently drains working memory capacity, and cognitive reserve is exhausted more quickly in complex listening situations (Rönnberg et al., 2013). Consequently, adults with SSD must depend upon visual cues and context to compensate for auditory mismatches, and the brain is pressurised by increasing cognitive effort for understanding speech, resulting in decreased overall cognitive resources and poorer working memory under noisy surroundings (Su et al., 2025). In SSD, the continuous effortful listening leads to hearing fatigue, where people feel physically and mentally drained after social interactions (Jeppsen & McMurray, 2025; Sahoo et al., 2025).

Clinical observations indicate that SSD patients are more likely to be exhausted after continual listening than those with bilateral hearing loss, partially because their better ear pushes them to be placed in more challenging environments without accommodations (Jeppsen & McMurray, 2025; Swain, 2024c). Using the better ear word scores in quiet looks acceptable, but SSD patients report increased effort and tiredness after prolonged listening, which is reproduced in poorer disability/handicap profiles on hearing-specific quality-of-life tools in unaided conditions (Shapiro et al., 2025). Due to tiredness rather than an inability to hear, this fatigue is extensively documented in pediatric populations where their academic performance is hampered (Bess & Tharpe, 1986b). Also, Bakkum et al. (2023) reported greater subjective fatigue in children with unilateral hearing loss without any amplification when compared with normal-hearing peers, and Bess et al. (2020) also documented elevated listening-related fatigue in children with SSD. Patient-reported fatigue is not just seen in children but is also severe in adults. Alhanbali et al. (2017) found that hearing-impaired adults, including SSD patients, described needing rest periods during the day (68%), energy depletion for evening activities (72%), trouble maintaining attention in lengthy meetings (78%), and cognitive load affecting overall quality of life (65%). McGarrigle et al. (2014) in their systematic review showed similar findings.

Hornsby (2013) utilised dual-task paradigms and demonstrated that adults with hearing loss & UHL patients showed significantly greater listening effort compared to normal-hearing individuals. SSD patients showed 15-25% worse secondary task performance, cognitive load was higher, as SNR decreased, listening effort increased, and fatigue effects summed over extended periods. As a trustworthy physiological indicator of cognitive load, Koelewijn et al. (2012) found that SSD patients display progressive and remarkably larger pupil dilations while administering speech-in-noise selective attention tasks, which correlate with self-reported listening effort (Pai et al., 2012; Wesarg et al., 2024). Electroencephalography findings by Bernstein et al. (2017) reported altered alpha oscillatory patterns in single-sided deafness individuals, more activity in the frontal cortical region during speech processing & reduced neural efficacy compared to normal-hearing controls.

Ultimately, long-term cognitive health may be hampered by this chronic listening effort. Lin et al. (2011) investigated the relation between hearing loss and cognitive decline, verifying that older adults with unilateral hearing loss showed a greater risk of cognitive deterioration compared to those with normal hearing. Hearing loss was individually associated with faster decline, and even mild hearing loss showed associations with cognitive effects. These clinical manifestations affect specific cognitive dimensions namely heightened demand on selective attention leads to difficulty ignoring background unwanted conversations, shortage of resources in working memory leads to failure in retaining and processing longer sentences, slower processing of complex instructions as a result of central reorganization of executive function, and prolonged mental energy fatigue results in withdrawal from social gatherings (Jeppsen & McMurray, 2025; Pai et al., 2012; Wesarg et al., 2024).

Tinnitus, Hyperacusis & Vertigo: The Aggravating Factor

Tinnitus is a highly prevalent and often bothersome comorbid condition in single-sided deafness; sometimes it is the main or initial complaint over hearing. Tinnitus and vertigo were recognised as the primary medical complaints among SSD patients more than hearing loss itself in the Indian clinical profile (Katiri et al., 2023c; Wesarg et al., 2024). Unilateral tinnitus occurs often in adults, affecting 60% - 85% of them (~60–75% (Baguley et al., 2013), 60-85% (Zeitler et al., 2015), 70-85% (Tyler et al., 2007), and 83% (Heyning et al., 2008). Interestingly, even if patients cannot hear with their affected ear, they typically report tinnitus localised to that ear (90%), contrasting with that side's silence (Jeppsen & McMurray, 2025; Rothpletz et al., 2012b; Snapp, 2019; Srinivasan et al., 2024a). Majorly, it is described as a constant, high-pitched tonal quality (60%), with severity ranging from mild to unbearable and correlating with the degree of hearing loss and onset timing (Baguley et al., 2013).

Without an external source, this perception of noise acts as an irritating factor that worsens discomfort and hearing difficulties (Andren et al., 2025). Arts et al. (2015) used the Tinnitus Handicap Inventory (THI) and measured a mean score of 38/100 (moderate handicap) in these individuals, & 25% of SSD patients had severe tinnitus with THI scores >56. Strong positive correlation was observed between THI and overall hearing handicap in adult (HHIA) scores (Wesarg et al., 2024). Tinnitus burden can have effects beyond hearing loss, leading to sleep disturbance (45%), concentration difficulties (52%), emotional distress (35%), anxiety, depression, and overall quality of life reduction (Baguley et al., 2013; Jeppsen & McMurray, 2025; Swain, 2024c). Alongside tinnitus, SSD patients show higher rates of hyperacusis ranging from 25 to 30% (Andersson et al., 2002), characterised by decreased loudness discomfort levels in the better ear & increased listening effort, which may reveal central auditory compensation mechanisms.

Depending on the pathology, SSD is commonly associated with aural sensation of fullness and vestibular disturbances, including occasional vertigo, disequilibrium, & balance disturbances (Denanto et al., 2022a; Jeppsen & McMurray, 2025; Snapp, 2019; Swain, 2024c). Merchant et al. (2008) and other researchers have documented how these symptoms vary by cause- sudden sensorineural hearing loss presents with an acute onset and definite time course. Rauch et al. (2012) and Chau et al. (2010) reported that these patients complain of an intense change in their hearing abilities (100%), instant localisation difficulties (95%), sudden consciousness of background noise interference (90%), and early tinnitus (Schreiber et al., 2010). They also experience aural fullness and vertigo or disequilibrium for a short span (40-60%). This leads to varying recovery patterns and higher rates of psychological distress due its sudden nature (Baguley et al., 2013).

In acoustic neuroma**,** there is a steady increase in tinnitus, which usually precedes hearing loss, and balance disorders are quite common (Zeitler et al., 2015). Post-surgically, Carlson et al. (2012) recognised that patients complain of complete hearing loss in the affected ear (50-95%), tinnitus (60-80%), associated vestibular dysfunction (60%), and possible facial nerve weakness affecting communication (10-30%), thus affecting quality of life.

Havia et al. (2004) stated that Ménière's disease shows symptoms of fluctuating hearing loss history before permanent SSD, tinnitus, aural fullness, & psychological impact of unpredictable fluctuations. Vestibular symptoms are exceptionally high in these patients, with 95% reporting vertigo or disequilibrium. In contrast, idiopathic single-sided deafness usually presents with only 20% mild vestibular symptoms (Merchant et al., 2005).

Psychosocial and Social Consequences in Adulthood

Irrespective of the underestimation of its influence in the past, current studies confirm that profound UHL and SSD have a notable impact on socialisation, job performance, and mental health and social well-being (Rothpletz et al., 2012; Swain, 2024c). The sounds reaching the poorer ear dampen, hinder speech intelligibility and spatial awareness, thereby creating significant safety risks such as failure to spot approaching vehicles or hazards towards their poorer ear, which leads to a chronic baseline of anxiety that ultimately leads to social withdrawal (Carlson et al., 2015; Denanto et al., 2022; Jeppsen & McMurray, 2025). SSD adults go through "Invisible" or "Hidden Handicap" that affects their work life and social relationships (Jeppsen & McMurray, 2025; Pantaleo et al., 2024b; Srinivasan et al., 2024). Patients also report anxiety, frustration, insecurity, irritability, embarrassment, relationship strain and withdrawal (Rothpletz et al., 2012; Swain, 2024c).

Research by Dwyer et al. (2014) highlights the prolonged daily obstacles faced by SSD patients. Patients frequently report directional confusion (85%) & misdirection when called (60%). Beyond these difficulties, their daily functioning & personal lives are severely affected, with vast majorities struggling to understand conversations at social gatherings (85%), when they take part in group discussions and meetings (72%), identifying active speakers in a group (70%), and sustaining social relationships (45%). As a result, most of them have reduced social engagement, chronic listening fatigue, tinnitus, and social withdrawal (Wie et al., 2010). Thus, avoidance behaviour is developed by these patients due to communication difficulties, leading to reduced participation in group sports, trouble in social dining, and a marked reduction in overall music appreciation and enjoyment (Hétu et al., 1988; Rothschild et al., 2013).

These communicative disabilities have a gradable impact on quality of life (QoL) and social well-being. Using tools like the Social Functioning Questionnaire (SFQ) and the Psychological General Well-Being Index (PGWBI), researchers indicate that SSD patients score lower in domains of general health, vitality, and positivity (Srinivasan et al., 2024). Vannson et al. (2015) and Gatehouse & Noble (2004) reported significantly lower SSQ scores, i.e., 15–25% lower, with reductions across all domains. In the work environment, SSD employees report feeling more tired and are frequently absent due to illness, likely a somatic manifestation of chronic listening stress (Srinivasan et al., 2024). Eventually, compared to bilateral hearing loss, SSD patients profoundly reduction in quality of life.

Prevalence in Adults

The prevalence of single-sided deafness is documented globally and nationally in numerous surveys and hospital-based studies. Golub et al. (2018) in a cross-sectional national epidemiological study of about 6,242 individuals covering NHANES cycles of 2005–2006, 2009–2010, and 2011–2012, estimated the total prevalence of UHL (defined as normal hearing ≤25 dB HL PTA in one ear and >25 dB HL in the other) in American adults at 7.2%, within which mild UHL was estimated around 5.7%, and moderate-or-worse UHL was estimated around 1.5%. UHL with moderate-or-worse hearing loss had hearing as a major Complain, however, the prevalence of hearing aid use among them (Golub et al., 2018). Strictly speaking, about the prevalence of severe-to-profound loss only, to maximise capture of sensorineural SSD & to rule out middle ear abnormalities, Kay-Rivest, and colleagues (2022) conducted a cross-sectional National Health and Nutrition Examination Survey study only for SSD with normal hearing (PTA ≤25 dB HL) in one ear and severe-to-profound loss (PTA >70 dB HL) in the other, estimated prevalence of 0.14% using a 4-frequency PTA, for approximately 345,064 American adults & by using a stricter 3-frequency PTA (500, 1000, 2000 Hz), the prevalence fell to 0.11%, approximately equal to 271,122 adults (Kay-Rivest et al., 2022).

In that same study, SSD was more prevalent among individuals aged 60–79 years and was slightly higher in women compared to men. Notably, 27% of adults with SSD self-reported "excellent" hearing regardless of their severe-to-profound unilateral loss, (Kay-Rivest et al., 2022). In the United Kingdom, the incidence of severe-to-profound SSD was estimated to be approximately 7,500 new adult cases annually, indicating that SSD is a significant audiological condition demanding structured rehabilitation planning (Baguley et al., 2006). Jun et al. (2015) analysed data from 18,650 participants in South Korea, Korea National Health and Nutrition Examination Survey (2010–2012), found that the prevalence of UHL was 9.31%, and UHL exhibited a weak correlation with ageing (Jun et al., 2015).

In a larger group study, Lee et al. (2020) defined UHL as PTA ≥41 dB in the worse ear and <41 dB in the better ear and estimated that 1,632 participants (weighted prevalence 5.55%) had UHL, and within these identified subjects, 56.86% had moderate hearing loss, 21.89% had moderately severe hearing loss, and 21.25% had severe-to-profound hearing loss. The adoption rate of the amplification device among these individuals was just 1.56% (Lee et al., 2020). Among adult-onset SSD patients in Japan, the most frequent cause was idiopathic sensorineural hearing loss (SSNHL), followed by various forms of otitis media and cerebellopontine angle tumours, confirming sensorineural dominance pathology (Usami et al., 2017).

In a rural population survey in India, Konadath et al. (2013) found that among individuals with audiological problems, 3.11% were identified as having unilateral hearing loss (Konadath et al., 2013). An important community-based survey was conducted by Konadath et al. (2017), investigating a total population of 22,558, identified hearing loss in 106 individuals, & 13 persons among them had unilateral hearing loss, revealing a SSD prevalence of 0.05% across all age groups (Konadath et al., 2017). At AIIMS Rishikesh, Bansal et al. (2016) reviewed audiometric data of 1,800 pure-tone audiograms in ENT OPD patients and indicated that among 802 SNHL (8.6%) cases, 257 (32.05%) had unilateral sensorineural hearing loss (USNHL) of which 155 patients (60.31%) had pure USNHL with normal hearing in the contralateral ear (Bansal et al., 2016). Gupta et al. (2021), reported that USNHL has been found to affect 7.9–13.3% of the Indian population. At the same time pointed out that the most common age group was 36–45 years (36.92%), there was no significant difference between right and left ear involvement, but males were predominantly affected than females (Gupta et al., 2021). In their retrospective analyses of audiological files from a tertiary hospital, Penwal et al. (2023) in Mumbai identified 185 patients with SSD (78 females, 107 males), yielding a hospital-based SSD prevalence of 4.15% (Penwal et al., 2024b). In their comprehensive institutional prevalence study on SSD from India at AIISH, Mysuru, Chowhan et al (2018) estimated the total number of SNHL cases over the four-year period, which was 11,534 and out of these, 225 cases were diagnosed with SSD, yielding an overall SSD prevalence of 1.95% (approximately 2 SSD cases per 100 SNHL cases. When divided by age group out of 225 SSD cases, adults from 19–59 years constituted the largest group at 60%, followed by adolescents from 13–18 years at 17.33%, children from 0–12 years at 14.22%, and geriatrics (>60 years) at 8.44% (Chowhan et al., 2018). Gender analysis revealed a male predominance, which is consistent with international studies by Tieri et al. (1988) and Oyler et al. (1988) (Shetty & Vishwaraj, 2024).

Solution for single-sided deafness

As patients with single-sided deafness face many challenges in real-life situations, and in a country like India, where it has a high prevalence of SSD, it mandates the urgent requirement for tailored rehabilitation to overcome these consequences for better speech understanding and to improve quality of life. Particularly, utilising the native language (such as Kannada) can help to accurately measure rehabilitation efficacy in high-noise environments, such as in India, where both noise and linguistic culture are more prevalent compared to other countries.

To examine the benefit of the rehabilitation, scenarios similar to real-life situations have to be examined, and the noise should mimic the noise that is present in the real environment. In literature, these have been examined by administering various speech-in-noise tests in these clinical populations. Among these, spatial release from masking is an important auditory mechanism that has been evaluated excessively in SSD, which assesses the binaural processes such as the head-shadow, binaural integration, binaural summation and binaural squelch (Litovsky, 2012). SRM with various amplification devices, such as the contralateral routing of signals system (CROS), bone-anchored hearing aids (BAHA), and cochlear implants (CI), has been extensively evaluated with varied differences in the type of stimuli and material used, and the following section discusses the same.

Defining spatial release of masking and its outcomes with amplification devices such as CROS, BAHA & CI

The Spatial Release from Masking (SRM) is one of the concepts in understanding and hearing speech in a noisy situation. SRM refers to the computable improvement in speech intelligibility that takes place when a target speech signal and competing masking noise are spatially separated in the sound field, as compared to a collocated condition where the target and masker come from the same position (Litovsky, 2012; Avan et al., 2015b; Denanto et al., 2022b; Srinivasan et al., 2024b; Rothpletz et al., 2012b).

Quantitatively, SRM is expressed as the difference in speech reception threshold (SRT) — the signal-to-noise ratio at which a listener achieves 50% sentence recognition — between the collocated reference condition (S0N0) and any spatially separated configuration (Garadat et al., 2009; Bronkhorst, 2000). Separating the signal and the masker in space allows listeners (with normal binaural hearing) to use interaural cues and head-shadow advantages to “unmask” the target speech when noise is moved off-axis. Under optimal conditions, normal-hearing adults yield substantial benefits, with SRM values as large as 10–15 dB (or ~12–15 dB in SNR), underscoring its profound everyday communicative relevance (Bronkhorst & Plomp, 1989; Pantaleo et al., 2024b).

For SSD patients, however, true spatial release is greatly reduced or absent without rehabilitation, since one ear receives no input. In SSD, listeners have only monaural input, so any benefit from spatial separation must come from a “better-ear” advantage or head shadow, not true binaural processing. Indeed, studies show that SSD (or unilateral hearing loss) listeners exhibit little or no SRM beyond what is afforded by head shadow (Srinivasan et al., 2024a). For example, Rothpletz et al. (2012) studied 12 unilateral hearing loss patients for informational masking and localisation task within an anechoic chamber using coordinate response measure (CRM) corpus stimuli and found that UHL subjects "did not exhibit a true spatial release from informational masking" – their performance was entirely predicted by which ear had the better signal-to-noise ratio (no additional binaural squelch benefit) at 0^0 target speech & both +/- 90° azimuth noise. In summary, SSD listeners suffer deficits in noisy, multi-source environments because they cannot use binaural squelch or summation, only a monaural head-shadow benefit (Pantaleo et al., 2024b; Sahoo et al., 2025).

There are amplification options that can benefit patients with single-sided deafness with audibility, but they come with their own limitations and drawbacks when tested for true spatial release from masking.

The head shadow benefit is the main and only established spatial benefit of CROS in SSD. By rerouting the signal from the poorer ear to the hearing ear, CROS hearing devices can reduce the negative impact of the head shadow for signals originating towards the poorer ear side. A significant head shadow benefit of approximately 1.7–2.2 dB SNR was observed in several studies when speech is directed towards the poorer ear (Snapp, 2019; Wesarg et al., 2024). A prospective, randomised crossover study by Mertens et al. (2018) comparing adhesive bone conduction with conventional CROS concluded that both devices improved sound awareness for signals directed at the poorer ear.

According to Ryu and her colleagues, when noise is presented towards the poorer ear side ($S^{AH}N^{SSD}$ and $S^{0}N^{SSD}$ conditions), CROS transfers that noise to the hearing ear, thus reducing the SNR at the functioning cochlea, but here the subjects were evaluated with three questionnaires, and there may be subjective variance.

The rerouting mechanism does not improve binaural processing since the CANS receive two varieties of the acoustic environment through a single cochlea, without the interaural comparisons required for binaural squelch. Another review by Peters et al. (2014) found no reliable improvement in speech perception in noise with CROS devices against the unaided listening condition. In a complex auditory task where the binaural cues are highly needed, binaural squelch is negligible when CROS hearing aids are used (Snapp, 2019).

CROS devices do not restore binaural summation because all auditory processing happens monaurally (through a single cochlea) and there is no true binaural redundancy (Pantaleo et al., 2024; Snapp, 2019). Wesarg et al. (2024) stated that no statistically significant summation effect was observed with CROS.

Snapp et al. (2017) found no significant improvement in sound localisation in the horizontal plane with CROS compared to unaided SSD. Snik et al. (2002) similarly reported chance-level sound localisation performance across all four conditions (unaided, CROS, CIC, and BAHA). CROS devices cannot return the natural binaural cues necessary for spatial processing that can be seen in normal individuals (Pantaleo et al., 2024b; Snapp, 2019).

Wesarg et al. (2024), in a prospective comparison involving 12 SSD adults using CROS, BAHA, and CI (at 6 months post-activation), the speech reception threshold (SRT) using the Oldenburg sentence test (OLSA) found a statistically significant decline in squelch of 2.9 dB ($S^{0}N^{SSD}$) and 3.2 dB ($S^{AH}N^{SSD}$) with CROS hearing devices, at 0^{0} target speech & both +/- 90° azimuth noise. He also found that SRM with CROS for two-talker babble noise was only 1.4 dB, significantly less than BAHA (3.0 dB) and CI (6.2 dB)

Importantly, when compared to BAHA, CROS did not show any statistical improvement in SRM, although both were significantly inferior to CI. No improvement was found with CROS when the masker was at the hearing side (+90° azimuth). This indicates a significant research gap, as the spatial release of masking is not achieved even when the spatial separations are vast.

BAHA offers a meaningful advantage in head shadow when speech is presented to the poorer ear and noise is presented to the better ear, with speech improvements supported by several well-established clinical studies. Snapp et al. (2017), in a cohort study of 27 single-sided deafness patients, showed significant improvement in speech perception in noise test, and concluded that there was no significant difference between CROS and bone-anchored implant (BAI) for objective speech-in-noise performance. A systematic review by Kim et al. (2017) of 296 patients across 14 studies, out of which 12 studies revealed that a favourable head shadow benefit was gained with BAHA for speech discrimination in noise. Wesarg et al. (2024) studied the binaural effect for unilateral bone conduction device users on either speech-shaped noise or two-talker babble maskers and found no statistically significant results. This indicates that the benefits of BAHA are more variable and might depend on the extent to which transcranial attenuation is achieved in each patient. Hol et al. (2002) found that 6 out of 10 patients benefited from BAHA over conventional CROS, with a moderate but actual head shadow effect.

BAHA reroutes the signal to the normal functioning cochlea and cannot bring back binaural squelch or summation. The essential requirement of independent signals from two separate cochleae for squelch is not met (Avan et al., 2015). This constraint is integral to the transcranial transmission mechanism. With a single device, the auditory system receives ambiguous interaural cues rather than true binaural input because vibrations spread to both cochleae with minimal ILD or ITD (Stenfelt, 2012; Stenfelt et al., 2026).

Many studies pooled by systematic review by conclude that BAHA do not improve sound localization ability in SSD (Kim et al., 2017; Peters et al., 2015). A systematic review by across six studies found no improvement in sound localization after BAHA implantation for SSD. Despite fitting BAHA, Douglas et al. (2007) in his study confirmed spatial hearing disability persists after acoustic neuroma removal. Similarly a study administered in right handed SSD showed correct localisation answers reached at best upto only 35% reported that, with no statistical difference between left- and right-implanted patients (Saliba et al., 2011).

Wesarg et al. (2024) found spatial release from masking of 3.0 dB in the multi-talker babble condition with BAHA, which was approximately double that of CROS (1.4 dB) but significantly less than CI (6.2 dB). As mentioned earlier, SRM with two devices, i.e., BAHA & CROS, was not statistically different from each other as there was no binaural benefit (squelch, summation). But, when bilateral bone conduction devices are used, a drastic improvement in SRM can be achieved (Stenfelt et al., 2026).

Although a bone-anchored hearing aid can bring about some spatial release of masking, it requires invasive surgery, and in a country like India with limited resources and economic constraints, people often deny opting for the device.

Literature on spatial release from masking with cochlear implant mainly highlights that true binaural input & spatial release from masking can be achieved with the device. In a landmark study that evaluated 11 CI users (normal hearing in one ear with SSD in the contralateral ear) using the OLSA sentence test in two-talker babble noise, with seven spatial configurations (noise from 0°, ±45°, ±90°; speech from front or ±90°), noted significant improvement in SRM, with binaural SRM exceeding monaural SRM by ~3 dB. This was the first study to prove that SRM can be restored in SSD using CI, and serves as a foundational reference in the field (Grossmann et al., 2016). When compared between 3 devices, i.e., CROS, BAHA, and CI, CI provided superior benefit than the other two devices & the only device that demonstrated all binaural effects. Head shadow benefits with CI were preserved even after long intervals (Wesarg et al., 2024). Williges et al. (2019) compared SRM in bimodal CI (CI + contralateral hearing aid) versus CI-SSD (CI + contralateral normal hearing) listeners. SRM significantly improved in both CI-SSD & bimodal CI users; with CI-SSD scoring higher than bimodal CI users, demonstrating that the presence of a contralateral normal hearing ear can maximise the binaural benefit from CI. CI users demonstrated improved SRT in spatially separated conditions, markedly better localisation performance and head shadow advantage compared to other rehabilitation options, which stays in line with previously discussed studies (Buss et al., 2018; Heteren et al., 2024).

Again, similar to the bone-anchored hearing aids, spatial release of masking is truly achieved by cochlear implants, but requires invasive surgery, is more expensive, may lead to loss of residual hearing, device failure or failure in osseointegration. Moreover, electrical stimulation and channel interaction can hamper ITD and ILD cues (Welch et al., 2018).

Digital Behind-the-Ear (BTE) Hearing Aids: Identifying the Research Gap

While devices like BAHAs and CIs exist, they are invasive and highly expensive, making them inaccessible in resource-constrained environments like India. Also, people are reluctant to go for surgery for their hearing loss in India. Digital behind-the-ear hearing aids provide conventional air conduction amplification. Digital BTE hearing aids are non-invasive and can be fitted without surgery (Kitterick et al., 2016) and have the capacity to give high-gain prescriptions compared to other styles of hearing aids.

BTE devices structurally minimize feedback by housing the microphone arrays and the digital signal processing (DSP) microchip within a casing that sits behind the pinna. This geometric separation between the microphone and the receiver drastically reduces the likelihood of mechanical and acoustic feedback.

Consequently, BTEs are uniquely capable of providing the high output necessary for SSD. BTE devices also position the microphone at the pinna level, which is the biologically optimal location for capturing the pinna's directional filtering effects (head-related transfer function, HRTF) (Dillon, 2001; Schuster-Bruce & Gosnell, 2022).

Preservation and Exploitation of Residual Hearing.

Digital BTE hearing aid can deliver substantial gain (up to 86 dB in high-power configurations) while keeping acoustic coupling to the poorer ear, for SSD patients with residual hearing at low frequencies (Sahoo et al., 2025). When residual hearing is present in the affected ear, a digital BTE hearing aid can restore audibility across the speech range, maintaining cochlear and central auditory pathway stimulation, and potentially guarding against auditory deprivation effects.

The BTE on the poorer hearing side acts as both a transmitter and a localised amplifier. By utilising a BTE to provide targeted amplification to the poorer ear, the auditory nerve continues to receive continuous acoustic neural firing, preserving the anatomical and physiological integrity of the spiral ganglion neurons and preventing maladaptive cortical reorganisation. Furthermore, BTE devices with custom vented earmoulds allow selective mid-to-high frequency amplification while preserving the natural resonance of the low-frequency residual hearing through the vent (Verma et al., 2017). The NAL-RP prescriptive procedure can also be implemented in digital BTE devices to provide wideband amplification while protecting these residual thresholds (Studebaker et al., 1991).

Low-Frequency Cues and Temporal Envelope Preservation.

Speech intelligibility is heavily dependent on the temporal envelope. Low-frequency auditory signals (below 250 Hz) enhance the perception of spectrally degraded speech by delivering fundamental acoustic cues such as voicing information, word segmentation cues, and sentence prosody (Nittrouer et al., 2014). In adults, the low-frequency residual hearing meaningfully improves speech perception in noise when acoustically amplified, which is supported by research on electric-acoustic stimulation (EAS) (Pillsbury et al., 2018). In bimodal listeners, low-frequency amplification below 500 Hz provides essential temporal and prosodic cues that electric stimulation alone cannot replicate (Zhang et al., 2010).

Modern digital BTE hearing aids can preserve temporal envelope integrity through several mechanisms. First, wide dynamic range compression (WDRC) with slow time constants better preserves envelope fluctuations (Moore, 2008). Second, BTE devices with high input dynamic range prevent saturation and peak clipping in analogue-to-digital converters (Kuk & Paludan-Müller, 2006). To prevent the smearing of vital acoustic cues, programming a BTE hearing aid with fewer channels or slower compression speeds better preserves the natural amplitude modulations that are critical for speech understanding (Moore, 2008).The loss of low-frequency information from the affected cochlea eliminates the temporal cues necessary for identifying the inter-aural time difference. Digital BTE hearing aids in the poorer ear can restore these ITD cues.

Cost-Effectiveness and Accessibility (Indian and Global Perspectives)

In India, individuals with single-sided deafness have a significant auditory and psychosocial handicap (Augustine et al., 2013), and it affects approximately 4.15% of patients in tertiary care settings (Sahoo et al., 2025). Patients often reject these devices due to a combination of high financial costs, cosmetic concerns, and underlying cultural stigmas (Augustine et al., 2013; Sahoo et al., 2025).

Conventional BTE hearing aids represent a very scalable, economically viable solution for hearing loss. Research by Verma et al. (2017) at AYJNIHH, India, reported statistically significant, longitudinal improvements in both functional gain and speech perception metrics following 6 to 24 months of continuous digital BTE amplification. A 2025 prospective study compared conventional high-gain hearing aids, CROS devices, and bone-conduction devices, confirming that conventional high-gain BTE hearing aids remain a feasible first-line option (Sahoo et al., 2025). Functioning solely as air-conduction acoustic amplifiers, conventional BTEs eliminate the need for surgery and related risks such as extrusion, osseointegration variables, and specific dental requirements, thus offering an immediate, non-invasive, and affordable rehabilitative option (Krishnan & Hyfte, 2016; Pantaleo et al., 2024b; Underdown & Pryce, 2022).

SRM and conventional digital BTE in adult patients with SSD

Research to date states that traditional BTEs fail to provide the binaural cues necessary for spatial unmasking (Ear Institute of Chicago, 2017). In patients with SSD, when aided with a conventional BTE, amplification of sound directly into the poorer ear cochlea yields no functional speech understanding or spatial awareness, but rather introduces an acoustic distortion that vigorously disrupts the signal (Ear Institute of Chicago, 2017).

Consequently, studies directly assessing conventional hearing aids in spatial tasks are rare and entirely restricted to the pediatric population or aidable unilateral hearing loss (UHL) rather than adult SSD. Evaluating these drawbacks, Ching et al. (2011) evaluated spatial release of masking in children with bilateral hearing loss using the Australian version of the Northwestern University-Children’s Perception of Speech test and Bamford-Kowal-Bench sentences in an eight-talker babble noise. They tested the 0° azimuth collocated condition and target signals from the front and babble noise from +/- 90° azimuth. Even though the SRM did not increase significantly, the materials used, such as NU-CHIPS and BKB-A sentences, are designed for children with a low vocabulary level and are easier for older children. They suffer from ceiling effects for listeners with only mild-to-moderate hearing loss, do not test linguistic complexity, and fail to accurately measure real-world listening difficulties (Miles et al., 2022; Vickers & Bradley, 2016). Also, +/- 90° azimuth maximum interaural time and level differences that easily improve signal-to-noise ratio (Ching et al., 2011). Native Australian children were studied, and the study was based on the native language. Hence, our study tries to mitigate these extremities and language barriers with Indian languages such as Kannada.

Similarly, Dawes et al. (2013) investigated SRM in seventeen new unilateral adult hearing aid users with mild to moderate hearing loss using British accent coordinate response measure (CRM) corpus stimuli and only three masker sentences found a non-statistical decrement in the aided SRM between the spatial conditions (0^0 azimuth & both +/- 90° azimuth). Even though adults were examined in the study, the material used can be easily learned by the participants as the stimuli are repeated, lack continuous context and require intervals (Eddins & Liu, 2012; Ozmeral & Higgins, 2022). Again, the language & speaker location used for the spatial release of masking is one of the limitations of this study, thus modified in our study.

Likewise, in Bishop et al.'s (2017) study, they investigated SRM patients with unilateral sensorineural hearing loss and moderate or worse hearing loss in the poorer ear, using Quick-SIN, NU-6 word lists, Abbreviated Profile of Hearing Aid Benefit & Speech, Spatial and Qualities of Hearing Scale 49. Their presentation of speech was to the better ear, and noise was directed to the poorer ear (180^0 to each other), vice versa and co-located conditions. First, the angle of separation between the target signals and noise is vast, and the listener's auditory system could naturally receive clear signals because of the head-shadow effect and the "selective better ear listening strategy". Second, the Quick Speech-in-Noise (QuickSIN) test uses short, one-syllable keyword sentences that heavily rely on American English syntax and vocabulary, and have very few sentences, which can lead to guesswork and the ceiling effect (Jovičić et al., 2016). NU-6 word lists have unfamiliar words that are not a part of everyday conversation (Thomson, 2002). The APHAB questionnaire measures the frequency of problems rather than the holistic quality or naturalness of the listening experience, and the extensive rating scales like SSQ49 allow for a high degree of subjective variance (Zhang et al., 2015).

A digital BTE hearing aid significantly improved localisation acuity in younger children with UHL and significantly poorer localisation acuity in older children. A significant correlation was found between age at intervention and the bilateral benefit. Children who were fit earlier showed bilateral benefit, whereas fit children later showed bilateral interference (Ching et al., 2011).

Development, however, may play a role in sound localisation acuity. When unaided, older children had significantly better localization acuity than younger children with UHL. A digital hearing aid can provide bilateral localisation benefit to some children with UHL. Early intervention may increase the likelihood of bilateral benefit. However, developmental factors appear to play a role in improving localisation abilities over time for children with UHL.

Nonetheless, without a means of establishing bilateral benefit with hearing aid amplification, localisation performance in children with UHL will rarely equal that of peers (Briggs et al., 2011; Ching et al., 2011; Corbin et al., 2017; Johnstone et al., 2010). The primary reasons for the complete lack of SRM benefit from conventional BTEs in SSD individuals comprise the absence of precise Interaural Time Differences (ITDs) and Interaural Level Differences (ILDs), severe frequency-based mismatch between the normal and aided ear, and the delayed & distorted digital signal that actively degrades the better ear's processing, which leads to binaural interference (Dawes et al., 2013).

A meticulous synthesis of the cited literature reveals overlapping, undeniable research gaps surrounding the rehabilitation of single-sided deafness (see Table 2.1). While SSD initiates a cascade of psychoacoustic deficits—obliterating the head-shadow advantage, binaural summation, and binaural squelch—the literature demonstrates that invasive devices like BAHA and CI face severe barriers regarding clinical evidence quality, anatomical limitations, and prohibitive costs, particularly in the Indian demographic landscape.
Untreated SSD inherently drives up

Table 2.1

Treatment Modalities, Their Disadvantages and Efficacy on True SRM

Treatment Modality	Disadvantages & Highlighted Gaps	Efficacy on True SRM
CROS Systems	Inconsistent benefits; degrades speech when noise targets the better ear; low patient adoption (Snapp, 2019).	No true SRM; it relies solely on shifting input.
BAHA / BCI	Invasive; relies on cross-head transmission masking ITD/ILD cues (Stenfelt et al., 2026). Material shortfalls in evidence (Baguley et al., 2006).	Minimal SRM; primarily provides monaural head shadow relief.
Cochlear Implants	Highly invasive; prohibitive costs globally; CI candidacy definitions are inconsistent (Vincent et al., 2015).	Provides measurable SRM improvements by restoring central binaural integration.
Digital BTE Hearing Aid	Historically abandoned due to distortion and binaural interference (Dawes et al., 2013). Major literature gap for aidable residual hearing outcomes (Bishop et al., 2017).	Under-researched in adult SSD populations using advanced spatial (S0N0, S0NB, S0NP) configurations.

cognitive load and listening effort, severely diminishing the quality of life and precipitating cognitive decline.

Simultaneously, the literature explicitly confirms a massive void concerning the efficacy of conventional, air-conduction hearing aids for SSD patients. As Bishop et al. (2017) formally declared, there is a fundamental gap in evaluating hearing aid outcomes for individuals with residual hearing in the affected ear.

Furthermore, Srinivasan et al. (2024) exposed the gap that current SRM testing methodologies utilise unrealistic spatial separations, emphasising the need to rigorously test smaller, ecologically valid spatial configurations like S0N0, S0NB, and S0NP setups.

Moreover, at +/- 60° azimuth, the sound is striking the near-side pinna at a perfect oblique angle. The unique ridges (like the helix and antihelix) seamlessly funnel those acoustic waves directly into the ear canal without them bouncing off the back of the head (Anthwal & Thompson, 2016; Stevenson-Hoare et al., 2022).

Finally, the diverse linguistic and cultural makeup of India, where SSD prevalence remains notably high (Chowhan, 2018), establishes a sociolinguistic gap since prior SRM studies have overwhelmingly utilised Western languages.

Addressing these explicit gaps underscores the absolute need for the proposed study. By investigating within-subject aided versus unaided SRM across defined spatial configurations using culturally specific Kannada stimuli, this research directly resolves the methodological and linguistic voids present in current literature.

More importantly, by exploring the potential of digital hearing aids, the study tries to bring up a scalable, cost-effective, and non-invasive alternative. The audiological outcomes derived will provide desperately needed evidence-based recommendations, informing clinical guidelines to alleviate cognitive fatigue and improve communication for millions affected by single-sided deafness within India's public health framework.

Chapter 3

Method

The primary objective of this study was to investigate & scientifically enumerate the audiological efficacy of Digital BTE hearing aid amplification on Speech Identification Scores (SIS) in three spatial conditions and then derive the extent to which Spatial Release from Masking (SRM) is occurring in adult individuals diagnosed with Single-Sided Deafness (SSD).

Study Design

A quantitative, cross-sectional and within-group repeated measures design was used to validate the objectives of the study.

Participants

A total of 11 adult participants were recruited for the study. The participants were selected using convenience sampling from the Department of Audiology at AIISH from November 2025 to May 2026. Participants were within the age range of 18 to 55 years (*M*= 42.64, *SD* = 8.97).

Inclusion criteria

i. All the participants had been diagnosed with single-sided deafness, defined as severe-to-profound sensorineural hearing loss, i.e., with a threshold of ≥ 70 dB HL in the poorer ear and normal or near normal hearing. i.e., with a threshold of ≤ 30 dB HL from 0.25 kHz to 8 kHz in the better ear (Heyning et al., 2016; Valente et al., 2006; Vincent et al., 2015).

ii. The speech identification scores (SIS) were ≥ 80% for Phonemically Balanced Kannada words in the better ear (Manjula et al., 2015).

iii. Those who had either 'A' or 'As' type tympanogram with the presence of acoustic reflexes in the better ear and

iv. Presence of otoacoustic emissions with a signal-to-noise ratio of 6 dB or more in at least two to three consecutive frequencies in the better ear, in either distortion product otoacoustic emissions (DPOAE) or transient evoked otoacoustic emissions (TEOAE) was involved.

v. Participants who were native speakers of Kannada, had no conductive/mixed/fluctuating hearing loss in both ears, and any neurological, cognitive, speech-language disorders or psychological abnormalities as assessed using an interview were included in the study.

Exclusion criteria

i. Individuals with conductive/mixed/fluctuating hearing loss.

ii. Individuals with any neurological, cognitive, speech-language disorders or psychological abnormalities as assessed using an interview.

Ethical considerations

All the study protocols were approved by the AIISH Institutional Review Board (Ref: SH/IRB/M.4/AUD.36/2025-26) before the data collection process (see Annexure I). Before evaluation, all participants received a detailed explanation of the study's aims and methodology, and written informed consent was obtained.

Test Environment

All tests were conducted in an electrically and acoustically protected double room, with ambient noise levels within acceptable bounds (ANSI S3.1, 1999).

Instrumentation & Software

1. A calibrated two-channel stand-alone audiometer, Otometrics Madsen Astra 2 (Inventis, Padova, Italy), was used to assess the participants' hearing status. Air-conduction and bone-conduction thresholds and speech audiometry were performed on all participants. An ER-3 or IP30 insert earphone (Radioear,

Middelfart, Denmark) was used for air-conduction testing and speech audiometry, and a B-71 bone vibrator (Radioear, Middelfart, Denmark) was used for bone-conduction testing.

2. Three calibrated Quilter Sound Company speakers were positioned at different speaker locations (0° azimuth, + 60° azimuth & - 60° azimuth/+300 ° azimuth), respectively. Participants were seated on a chair, at a distance of 1 meter from all the speakers.
3. A calibrated GSI Tympstar Pro (Grason-Stadler, Inc., Eden Prairie, United States) was used to measure tympanometry at a 226 Hz probe tone and acoustic reflex thresholds at 500 Hz, 1 kHz, 2 kHz, and 4 kHz for all participants in ipsilateral and contralateral modes.
4. DPOAE or TEOAE was recorded using an ILO v6 calibrated otoacoustic emission analyser (Otodynamics, Ltd., Hatfield, UK).
5. A digital programmable Danavox Klar 498 DW SP BTE (GN Hearing A/S, Ballerup, Denmark) hearing aid was used for the experiment for the aided condition. A HP desktop installed with NOAH 4 (HIMSA, Copenhagen, Denmark) and NOAHlink Wireless 2 programmer (HIMSA, Copenhagen, Denmark) was used to program the hearing aid.

Test Stimuli

i. PB words in Kannada (Manjula et al., 2015). A total of 25 words in each list

ii. Multi-talker babble (Nayana et al., 2018). The multi-talker babble consisted of 4 female talkers.

Six recorded lists of phonemically balanced Kannada words (Manjula et al., 2015) were used. Each word list was presented to each patient in random order. were presented in each listening condition via the audiometer, using channel 1, both with and without a hearing aid. A multi-talker babble (Nayana et al., 2018) was presented through the audiometer via channel 2. Both speech stimuli & noise were played at the same intensity, i.e., at 40 dB HL, therefore maintaining the signal-to-noise ratio of 0 dB.

Basic Audiological Evaluation

i. A detailed case history was taken.
ii. An otoscopic examination was conducted to rule out impacted wax and other external ear pathologies.
iii. Pure tone audiometry: The hearing thresholds for each participant were assessed through both air conduction (250Hz – 8kHz) and bone conduction (250Hz - 4kHz) using a modified version of the Hughson and Westlake method (Carhart & Jerger, 1959).
iv. Speech Identification Scores were obtained by using Phonetically Balanced Kannada words (Manjula et al., 2015)
v. Tympanometry was performed using 226 Hz and acoustic reflexes at 500 Hz, 1 kHz, 2 kHz, and 4 kHz in the ipsilateral and contralateral modes.
vi. TEOAEs were recorded using 260 sweeps of linear click trains presented at 80dB pe SPL, and DPOAEs were recorded using two simultaneous pure tone stimuli presented with f1 = 65 dB HL and f2 = 55 dB HL, maintaining a f2:f1 ratio of 1.22, observed from 1 kHz to 6 kHz.

Procedure

Preliminary assessment procedures

A basic audiological evaluation was performed, and the participant's hearing thresholds were measured to determine whether they met the inclusion criteria. The participant was informed about the experimental procedure, and only if he/she was willing to participate in the experiment was he/she taken for the study. Finally, informed consent was taken before the test began.

Instant ear mould

As the poorer ear has to be fitted with a hearing aid, instant earmolds were used, which were custom-made and created directly from ear impressions of the participants to ensure precise fitting, reducing feedback and data accuracy for the study.

Hearing aid programming

The poorer ear of each participant was aided, to make use of residual hearing, with a digitally programmable BTE hearing aid (Danavox Klar 498 DW SP BTE) attached to a custom-made shell instant earmold for optimal acoustic seal and feedback prevention. The participant's pure tone audiogram thresholds for each frequency were updated & the hearing aid was programmed using hearing aid-specific software (BeMore XE) on a personal computer. When the hearing aid was switched on and worn by the participant, it was connected via the NOAHlink Wireless 2 programmer, and the programming software would detect the hearing aid.

The hearing thresholds of each participant were entered into the programming software, and target gain curves were obtained using the proprietary prescription formula of the hearing aid. The hearing aid gain was further fine-tuned based on the audibility of Ling's six sounds. To ensure that the hearing aid provided the most appropriate amplification, the participants were asked to repeat Ling's six sounds presented randomly (/a/, /i/, /u/, /s/, /sh/ and /m/). The gain was adjusted for audibility of at least a few Ling's six sounds or just below the feedback oscillation. A feedback test was run, and feedback cancellation was activated if any trace of feedback was detected, to ensure stable amplification without oscillation. The hearing aid microphone was set to omnidirectional mode to capture sounds equally from all directions, avoiding any alteration of interaural level differences (ILDs) that directional mics might introduce (Ricketts & Mueller, 2000). Digital noise reduction (DNR) and other adaptive features (e.g., wind noise reduction, impulse noise suppression, or adaptive compression) were switched on.

Acclimatization

Participants had to undergo a short acclimatisation period (5-10 minutes) with the aided setup before initiating the actual test procedure. Participants sat comfortably in the chair. A standardised passage in Kannada (Savithri et al., 2005) was presented for familiarising with the hearing aid, through the audiometer using channel 1 via the front speaker (0° azimuth) at 40 dB HL & the patient had to passively listen to the passage through the speaker.

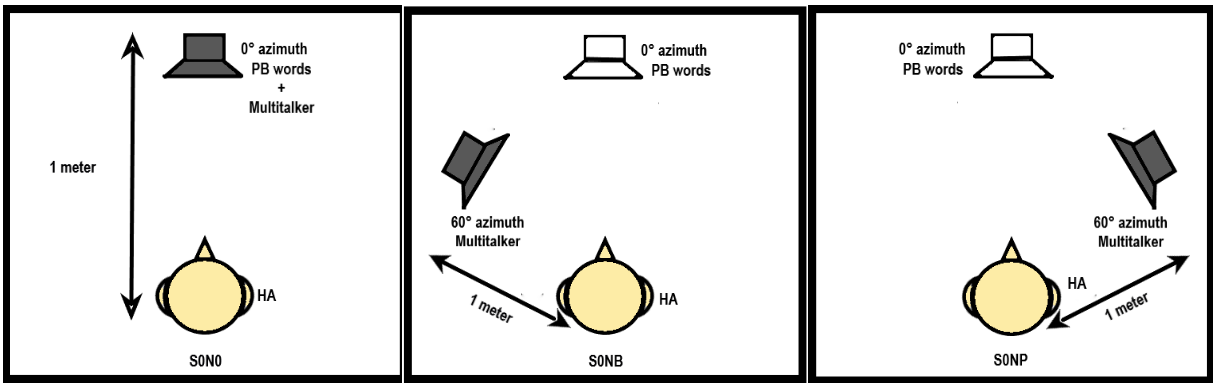
Experimental procedure

Test set-up

Testing was carried out inside a sound-treated booth, where participants were seated on a chair placed at a distance of 1 m from the loudspeakers and instructed to maintain a forward-facing head position throughout the task (see Figure 3.1).

Figure 3.1

Test set-up



Note. The above figure represents the spatial orientation of the speakers & participants' seating arrangement between the speakers. The components of the image read as follows: White speaker = Target stimuli or PB *w*ords; Grey speaker = Noise or Multitalker Babble; HA = Poorer ear fitted with hearing aid; Listening conditions: S0N0 = Collocated; S0NB = Words towards the front and noise towards the better ear; S0NP = Words towards the front and noise towards the poorer ear.

The participants were instructed as follows:

Instructions

'You will be seated on the chair, between three loudspeakers. Next, you will have to attend carefully and listen to a few words. Simultaneously, you will be hearing background chatting, like a busy market or coffee shop. Your task is to focus only on the words. Please try to repeat whatever you've heard. You can guess the words if you are not sure. Then, you must wear the hearing aid (in the poorer ear). In the beginning, you will hear a Kannada passage, to which you have to just passively listen, and you need not respond to it. Again, you have to listen to a few words in the presence of background chatting, only focus on the words and try to repeat whatever you've heard. Do you have any queries/questions?'

Procedure

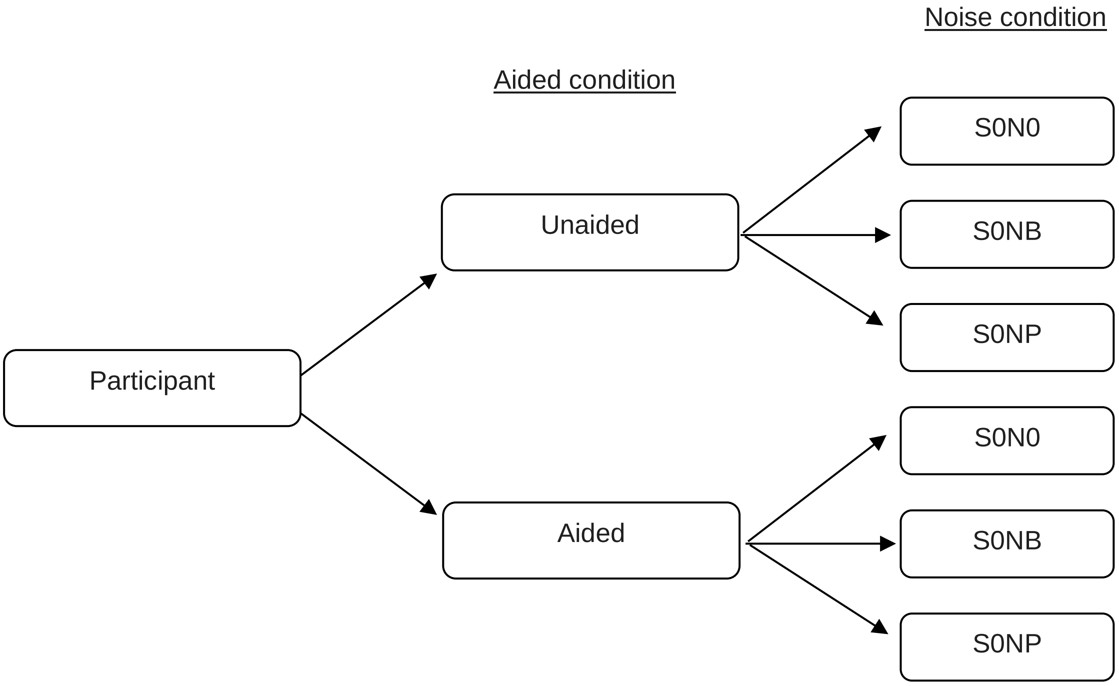
The experimental task involved listening to target speech stimuli (recorded PB words) presented from the front loudspeaker and repeating them aloud in the presence of multi-talker babble noise. The participant was subjected to 2 listening conditions (aided vs unaided) and 3 spatial conditions (front vs better ear vs poorer ear). The order of aided (& unaided)) and noise conditions (S0N0, S0NB, S0NP) were counterbalanced and randomised across participants to minimise order effects and ensure unbiased results (see Figure 3.2).

- S0N0: Both words and noise are presented towards the front.
- S0NB: The words are presented towards the front, and noise is towards the better/sound ear.

- S0NP: The words are presented towards the front, and noise is towards the poorer ear.

Figure 3.2

Listening Conditions & the Spatial Configurations



The same procedure was followed with the aided condition. Spatial releases from masking (SRM) were computed by comparing SIS across spatial conditions. SRM toward the better ear (SRM_B) was calculated as the difference between SIS obtained in the S0NB condition and that in the S0N0 condition (SRM_B = SIS in S0NB − SIS in S0N0) (Figure 3.3). Similarly, SRM toward the poorer ear (SRM_P) was derived as the difference between SIS in the S0NP condition and SIS in the S0N0 condition (SRM_P = SIS in S0NP − SIS in S0N0) (Figure 3.4). These calculations were performed separately for the unaided and aided conditions. Figure 3.5 represents the complete workflow of the study.

Figure 3.3

Flow-Chart for Calculating Spatial Release of Masking for Better ear Condition

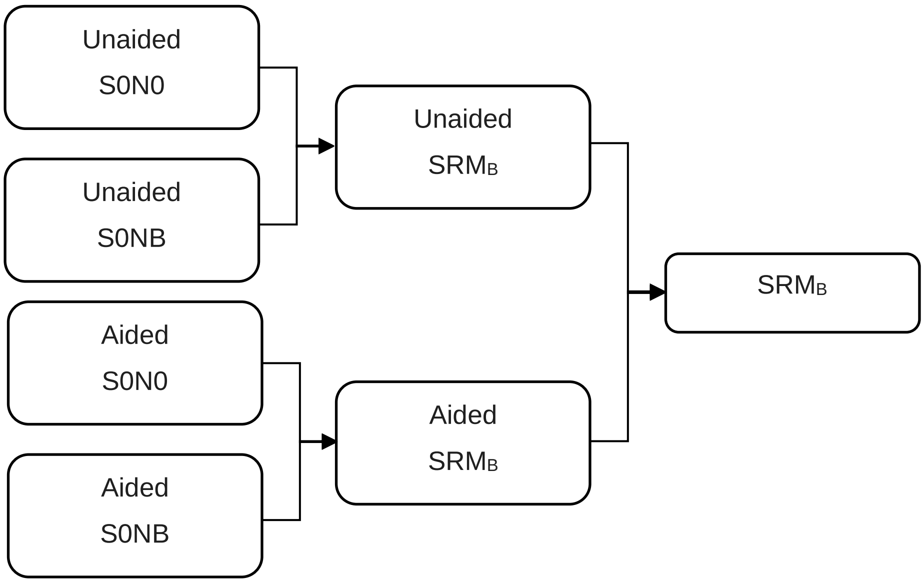


Figure 3.4

Flow-Chart for Calculating Spatial Release of Masking for Poorer ear Condition

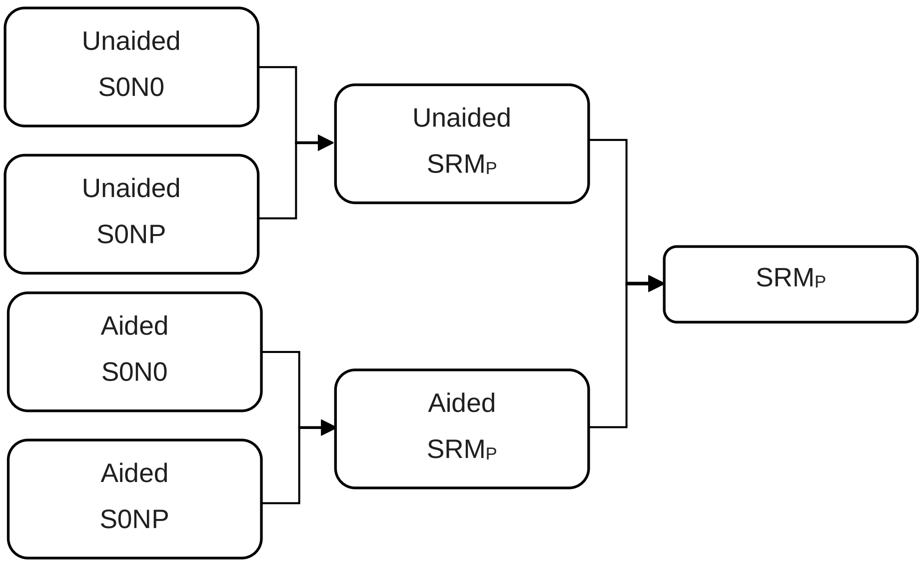
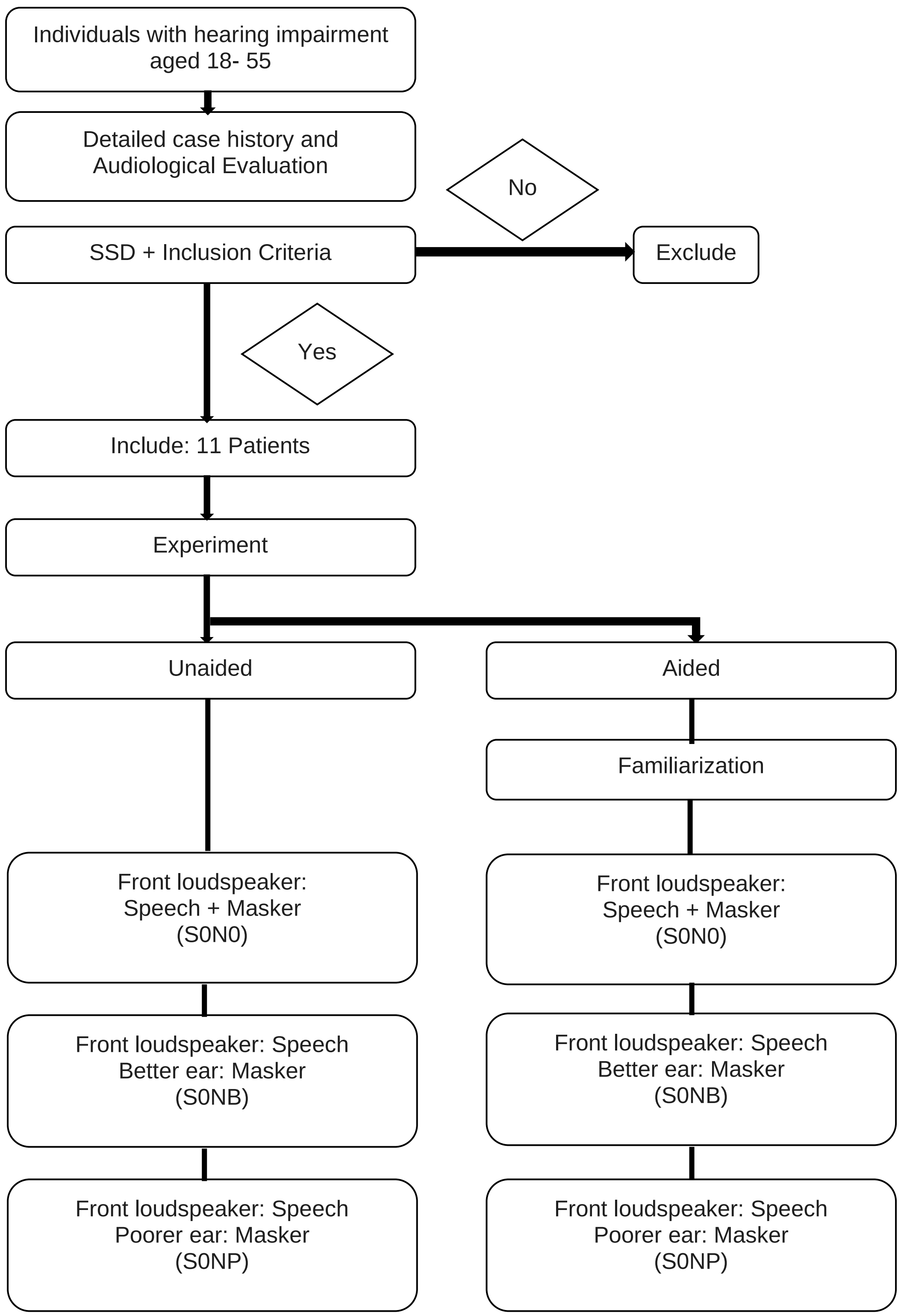


Figure 3.5

Complete Workflow Of The Study



Scoring

A total of 25 PB words in Kannada were presented for each spatial condition in the listening condition. Each correctly identified word was scored '1', each incorrectly identified word was scored '0' and 'NR' was marked for no response.

Statistical Analysis

All the statistical analyses were done using IBM SPSS v.26. The obtained data were tabulated. Further, examined for normality using Shapiro-Wilk's test. As the data followed normal distribution, a paired t-test was performed to find out the differences in score between the aided and the unaided SIS at three spatial conditions. Wilcoxon's signed rank test was performed to assess the differences in SRM obtained under aided and unaided conditions.

Chapter 4

Results

The primary objective of this study was to quantify the Speech Identification Scores (SIS) in aided & unaided conditions across a collocated spatial configuration (S0N0) and two spatially separated configurations: masking noise directed toward the better ear (S0NB) and masking noise directed toward the poorer ear (S0NP). The secondary aim was to derive the magnitude of Spatial Release from Masking (SRM) in adult individuals diagnosed with Single-Sided Deafness (SSD) with and without a hearing aid.

The Shapiro-Wilk test of normality was applied to check deviations from normality in the sample collected. All variables were normally distributed (p >0.05), except unaided and aided SRM_B, unaided and aided SRM_P ($p < 0.05$). To ensure maximum statistical rigour, a combination of parametric and non-parametric techniques was employed to examine the within-subject variances between the unaided and aided listening conditions.

Participant demographics

Data were extracted, compiled, and analysed for a total cohort of *(N*=11*)* adult participants strictly diagnosed with SSD. The selected sample comprised 6 females and 4 males, representing a diverse cross-section of the adult population with chronological ages ranging from 26 to 52 years (*M*= 42.64, *SD* = 8.97). Table 4.1 summarises the baseline audiological profiling of the clients.

Speech identification scores across spatial configurations

Descriptive statistics were performed to obtain the mean and standard deviations of each listening condition, i.e., S0N0, S0NB and S0NB across aided and unaided conditions.

The mean Speech Identification Scores (SIS) varied across aided and unaided conditions under different noise conditions. In the unaided condition, the highest mean SIS

Table 4.1

Summary of Participant Demographics and Baseline Audiological Characteristics

Sl.No.	Age (Years)	Gender	Poorer Ear	Degree of HL* (Poorer Ear)	Degree of HL (Better Ear)
1	52	Male	Right	Severe SNHL†	Minimal SNHL
2	26	Female	Left	Profound SNHL	Normal
3	45	Male	Right	Severe SNHL	Minimal SNHL
4	52	Male	Left	Profound SNHL	Minimal SNHL
5	46	Female	Left	Severe SNHL	Normal
6	52	Female	Right	Profound SNHL	Minimal SNHL
7	42	Male	Left	Profound SNHL	Normal
8	31	Female	Right	Profound SNHL	Normal
9	39	Female	Right	Profound SNHL	Normal
10	49	Female	Left	Severe SNHL	Normal
11	35	Female	Left	Profound SNHL	Minimal SNHL

Note. * HL= Hearing Loss, †SNHL= Sensori-Neural Hearing Loss

was observed in the S0NB condition, followed by S0NP, while the lowest score was obtained in S0N0.

In the aided condition, SIS improved across all listening conditions compared to the unaided condition. The highest mean SIS was observed in the S0NP condition, followed by S0NB and S0N0.

Overall, participants demonstrated better speech identification performance in the aided condition relative to the unaided condition across all noise conditions (Table 4.2).

A paired t-test was conducted to compare the SIS obtained in aided and unaided conditions across the listening conditions (S0N0, S0NB, and S0NP).

Table 4.2

Mean and standard deviation of Speech Identification Scores (SIS) Across Listening and aided Conditions

		SIS (Maximum = 25)	
Listening conditions	Noise conditions	Mean	Standard deviation
Unaided conditions	S0N0	11.18	2.601
	S0NB	13.55	5.203
	S0NP	12.36	4.843
Aided conditions	S0N0	14.00	2.828
	S0NB	14.82	6.274
	S0NP	15.64	4.130

Co-located Speech and Noise presented at 0^0 azimuth (S0N0)

In this configuration, both the speech and multi-talker babble were presented from the front (0^0 azimuth). The mean unaided SIS and aided SIS are presented in Table 4.2 and Figure 4.1. The mean unaided SIS was 11.18 (*SD* = 2.601) and the mean aided SIS was 14.00 (*SD* = 2.828). The SIS was greater in the aided condition compared to the unaided condition.

A paired-samples *t*-test revealed a statistically significant difference in SIS between the aided condition and unaided conditions [t (10) = 3.96, p = .003, d = 1.03]. This indicates a large effect (Table 4.3).

Table 4.3

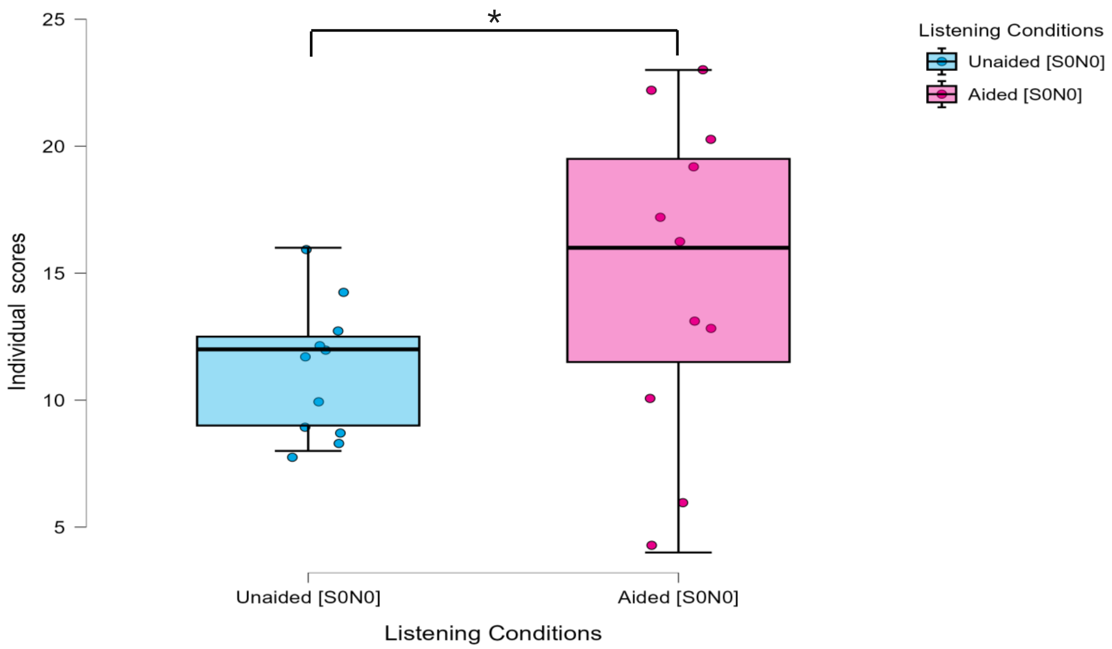
Paired-Samples t-Test Outcomes for Speech Identification Scores Across Spatial Conditions

Aided vs Unaided	*t*	*p*	Cohen's d
S0N0	3.963	.003	1.03
S0NB	1.617	.137	0.203
S0NP	3.157	.010	0.716

Figure 4.1

Individual SIS, Mean SIS & Standard deviation for Unaided & Aided Conditions at S0N0 condition

The figure items read as follows: The data points indicate the particular individual's scores. Also, aided and unaided scores are depicted for understanding each individual's performance. In the box plots the center line indicates the mean and the shaded region indicates the standard deviation of both aided and unaided listening conditions.



Note. * Significant Difference (*p* < .005). X- axis = Individual SIS (Max. 25), Y- axis = Listening conditions

Spatial Separation: Masker Directed Towards the Poorer Ear (S0NP)

In this configuration, the competing multi-talker babble was directed toward the poorer ear (+/- 60° azimuth), whereas noise was presented at 0^0 azimuth. The mean unaided and aided SIS is presented in Table 4.3 and Figure 4.2. The mean unaided SIS was 12.36 (*SD*

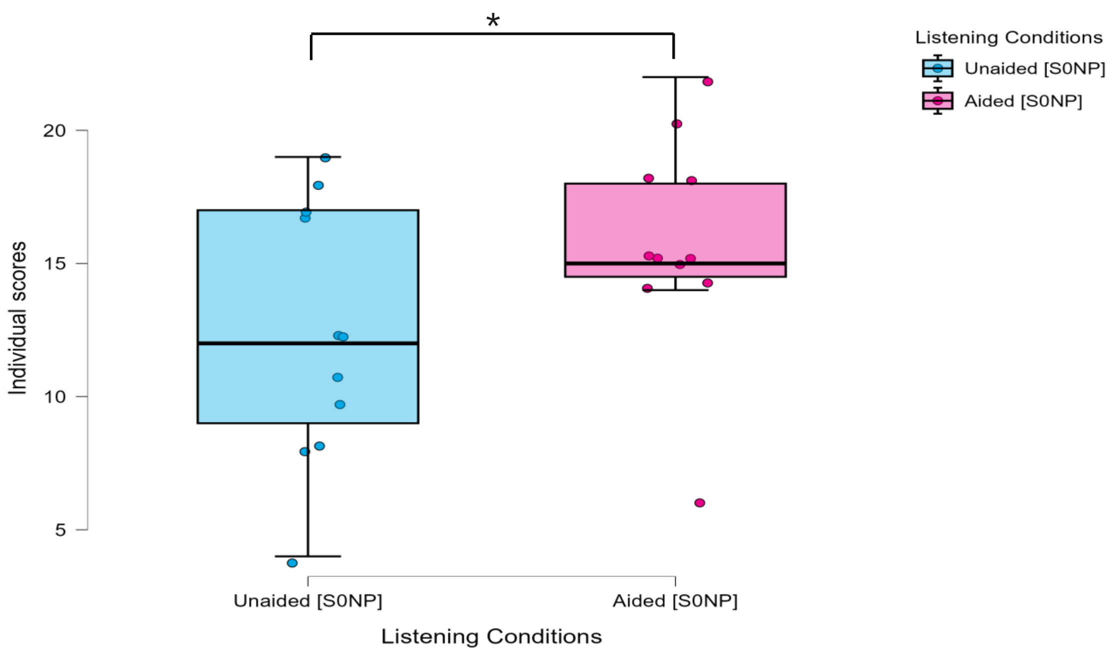
= 4.843) and the mean aided SIS was 15.64 (*SD* = 4.130). Clearly, the SIS was greater in the aided condition compared to the unaided condition.

The paired-samples *t*-test findings indicated that the differences in SIS were statistically significant, with higher scores obtained in aided conditions [*t* (10) = 3.16, *p* = .010, *d* = 0.716]. This indicates a moderate effect (Table 4.3).

Figure 4.2

Individual SIS, Mean SIS & Standard deviation at S0NP condition

The figure items read as follows: The data points indicate the particular individual's scores. Also, aided and unaided scores are depicted for understanding each individual's performance. In the box plots the center line indicates the mean and the shaded region indicates the standard deviation of both aided and unaided listening conditions.



Note. * Significant Difference (*p* < .005). X- axis = Individual SIS (Max. 25), Y- axis = Listening conditions.

Spatial Separation: Masker Directed Towards the Better Ear (S0NB)

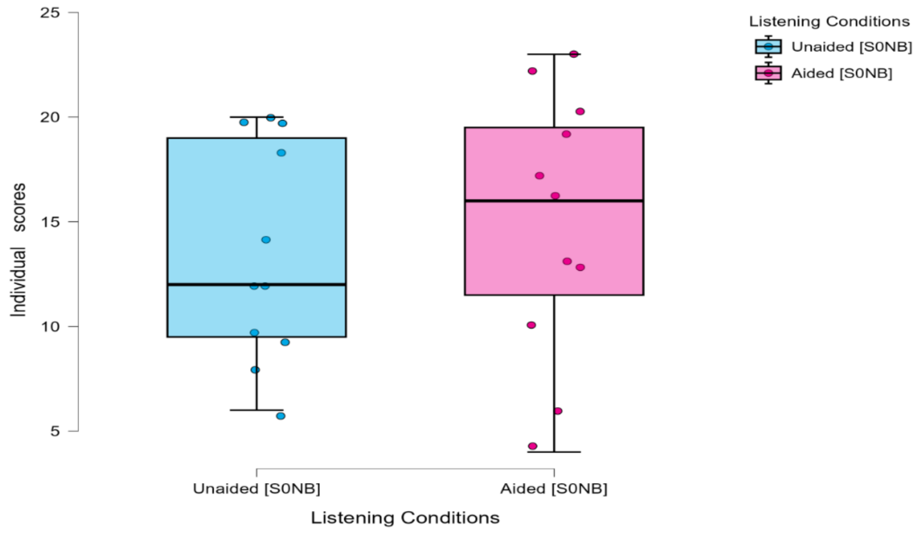
In this configuration, the multi-talker babble was presented to the better ear (+/- 60° azimuth), and speech was presented from 0^0 azimuth. The mean unaided SIS and aided SIS is presented in Table 4.3 & Figure 4.3. The mean unaided SIS was 13.55 (*SD* = 5.203) and the mean aided SIS was 14.82 (*SD* = 6.274). The SIS improved marginally in the aided condition compared to the unaided condition.

The paired-samples *t*-test indicated no significant difference between SIS obtained in aided and unaided conditions, *t* (10) = 1.617, *p* = .137, *d* = 0.203 (Table 4.3).

Figure 4.3

Individual SIS, Mean SIS & Standard deviation at S0NB condition

The figure items read as follows: The data points indicate the particular individual's scores. Also, aided and unaided scores are depicted for understanding each individual's performance. In the box plots, the center line indicates the mean and the shaded region indicates the standard deviation of both aided and unaided listening conditions.



Note. X- axis = Individual SIS (Max. 25), Y- axis = Listening conditions.

Spatial Release from Masking (SRM)

Spatial Release from Masking (SRM) is derived from S0N0 and S0NB for better ear, similarly, S0N0 and S0NP for poorer ear separately for aided and unaided condition. The median and interquartile ranges of SRM for both better and poorer ear are presented in Table 4.4 and Figure 4.4 & 4.5.

The median unaided SRM_B was 2 (*IQR* = 4), and the median aided SRM_B was 1 (*IQR* = 4). The median unaided SRM_P was 1 (*IQR* = 3) and the median aided SRM_B was 2 (*IQR* = 4). Also, the median SRM_B was -1 (*IQR* = 1.5), and the median SRM_P was 1 (*IQR* = 6). SRM_B did not improve in the aided condition compared to the unaided condition, but for SRM_P there was a marginal improvement in the aided condition.

A Wilcoxon signed-rank test was conducted to determine the significant differences in SRM obtained for the aided and unaided conditions. For the SRM at better ear and poorer ear condition (SRM_B & SRM_P), the results revealed that the unaided scores were not statistically significant from the aided scores for better ear ($z = 1.44$, $p = 0.17$) and poorer ear ($z = 0.36$, $p = .76$).

Table 4.4

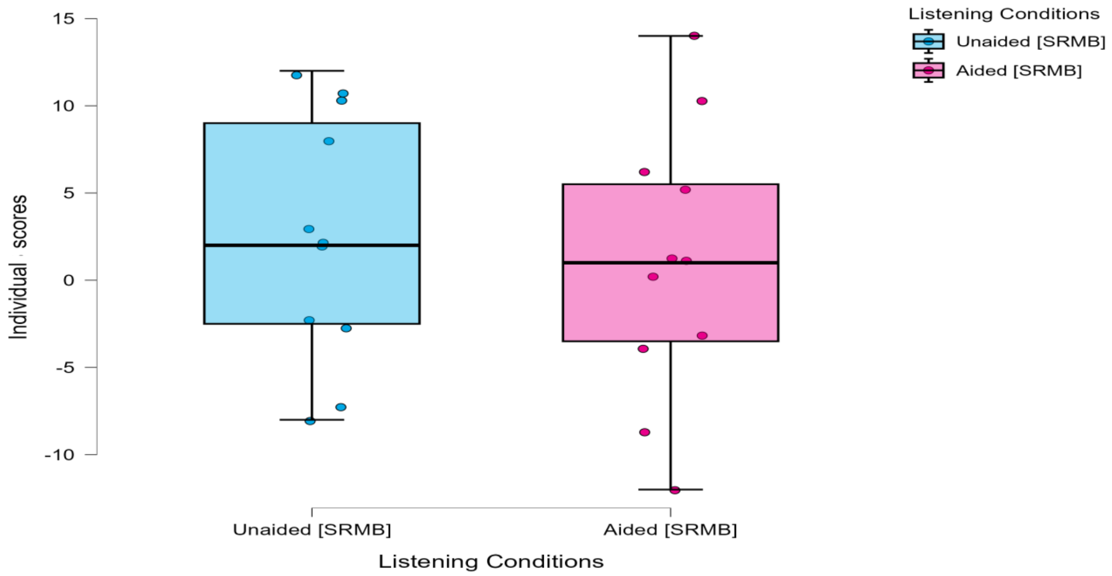
Comparisons of Spatial Release from Masking (SRM) for Aided and Unaided Conditions between Spatial Configurations

Pairs	Median	*IQR*	*z*	*p*
Aided vs Unaided SRM_B	-1	1.5	1.427	0.165
Aided vs Unaided SRM_P	1	6	0.357	0.759

Figure 4.4

Individual, Median & Interquartile Range of SRM for Unaided & Aided Conditions between the Spatial Configurations in Better ear

The figure items read as follows: The data points indicate the particular individual's scores. Also, aided and unaided scores are depicted for understanding each individual's performance. In the box plots the center line indicates the median and the whiskers indicate the interquartile range of both aided and unaided listening conditions.

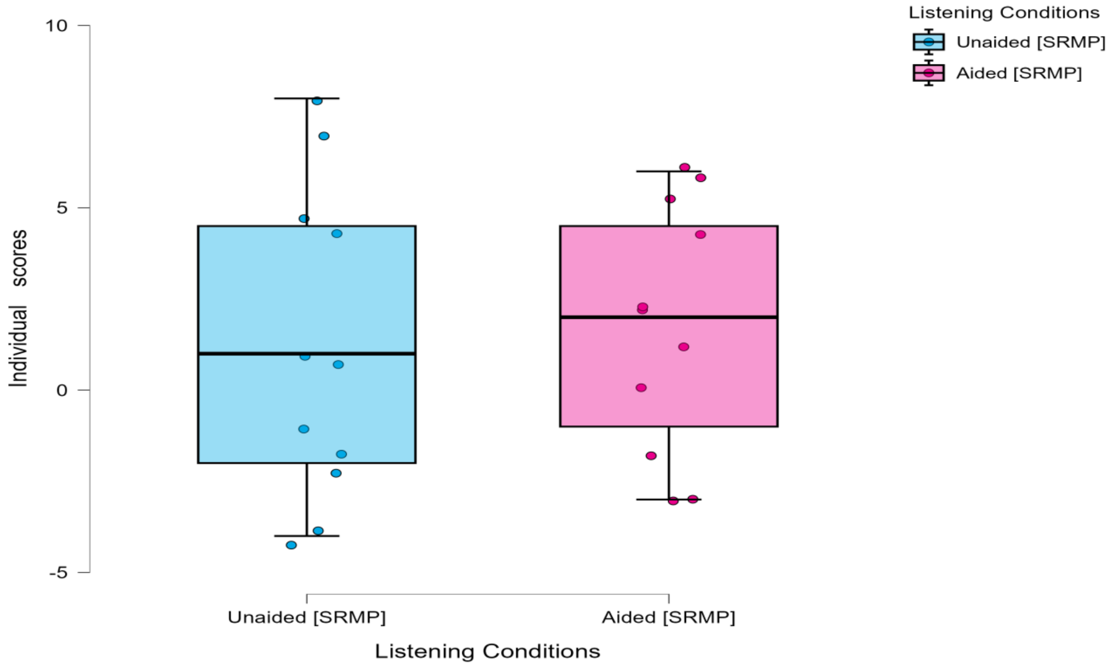


Note. X- axis = Individual SIS (Max. 25), Y- axis = Listening conditions.

Figure 4.4

Individual SIS, Median & Interquartile Range of SRM for Unaided & Aided Conditions between the Spatial Configurations in Better ear

The figure items read as follows: The data points indicate the particular individual's scores. Also, aided and unaided scores are depicted for understanding each individual's performance. In the box plots the center line indicates the median and the whiskers indicate the interquartile range of both aided and unaided listening conditions.



Note. X- axis = Individual SIS (Max. 25), Y- axis = Listening conditions.

Chapter 5

Discussion

The current study aimed to investigate the effect of the aided condition on spatial release from masking among individuals with single-sided deafness. The investigation specifically focused on the amount of Spatial Release from Masking (SRM) using Kannada PB words as target stimuli and four talker babble noises.

Better scores in the aided condition compared to the unaided condition

The findings of the present study indicated that the aided scores are significantly higher than the unaided scores across all noise configurations.

The finding is consistent with Bishop et al. (2017), who reported improvement in speech intelligibility index with the hearing aid among patients with unilateral sensorineural hearing loss. Stimuli used were Quick-SIN, NU-6 word lists, APHAB & SSQ49.

Similarly, the finding is consistent with the observations of Anderson et al. (2022) and Park et al. (2021), who reported that interventions providing direct acoustic or electrical stimulation to the poorer ear in SSD resulted in improvements in speech perception in noise.

A similar finding was observed in Dawes et al. (2013) study, which investigated SRM in 17 naïve unilateral hearing aid users with mild to moderate hearing loss using the coordinate response measure (CRM) corpus stimuli and found that speech identification thresholds were 1-6 dB lower than unaided thresholds.

Among individuals with SSD, the cognitive load required to decode degraded speech from babble is high and results in profound listening fatigue (Shetty, 2017). Hornsby noted that the use of clinically fit hearing aids may reduce listening effort and susceptibility to mental fatigue associated with sustained speech-processing demands while administering a dual task paradigm in mild to severe sensorineural hearing loss patients (Hornsby, 2013).

Aiding the poorer ear reintroduces audibility by amplifying the acoustic signal via digital hearing aids (Keidser et al., 2011). Further, the hearing aid preserves the raw envelope and temporal fine structure of both the speech and noise stimuli (Pieper et al., 2022).

The statistically significant improvements in raw SIS with the babble strongly suggest that amplification effectively reduces the cognitive listening effort required to actively unmask the target signal.

Speech identification scores significantly improved when the masker was directed towards the poorer ear (S0N0)

The findings of the current study indicated that there was a significant improvement in the aided S0N0 condition. This again suggests that restoring audibility to the poorer ear facilitated an effective binaural redundancy. This finding was in contradiction to the study done by Bishop et al. (2017). They reported that the speech intelligibility was reduced in the aided condition, when speech and noise were collocated, as the hearing aid amplification could not separate the target sentence from noise.

In the unaided condition, due to the sensorineural hearing loss in one ear, the advantage of binaural summation is lost. Lack of bilateral input forces the central auditory nervous system to rely only on one ear to extract the target words from the babble, yet fails to separate them effectively (Bishop et al., 2017).

On the other hand, in aided condition, the conventional hearing aid was successful in preserving the acoustic envelope and temporal fine structure of both the target words and the multi-talker babble (Pieper et al., 2022). The auditory system was capable of integrating the poorer ear signal with the contralateral better ear cues, which led to a remarkable increase in their absolute SIS in the aided condition.

Speech identification scores significantly improved when the masker was directed

towards the poorer ear (S0NP)

Further, the findings of the study indicated that the participants exhibited a significant improvement in their SIS when multi-talker babble noise was directed to the side of the poorer ear (S0NP). This finding is consistent with Bishop et al. (2017) study, where the patients with unilateral sensorineural hearing loss had improved scores on Quick-SIN, NU-6-word lists, APHAB & SSQ49. These results highlight the complex interaction between restoration of audibility and the natural acoustic head shadow effect.

In an unaided condition, when babble is directed toward the poorer ear, the human head naturally acts as a physical acoustic baffle, attenuating high-frequency noise components before they can physically diffract and reach the contralateral better hearing ear. This physical, acoustic phenomenon creates a better SNR at the better ear (Kumpik & King, 2019; Bishop et al., 2017).

On the other hand, when the poorer ear is aided with a hearing aid, it further amplifies the babble presented in the poorer ear. Paradoxically, the amplification of the babble would degrade central performance by introducing informational and energetic masking into the central auditory system (Bishop et al., 2017; Roushan et al., 2026). Yet, there is improvement in SIS in the S0NP condition when aided.

This improvement might be attributed to the fact that the primary target speech, which is arriving from the front speaker (0°), is also being amplified by the BTE device. The central auditory system appears to continuously attend to the high-fidelity speech signal arriving at the better ear. While simultaneously utilising the amplified, distorted signal from the poorer ear for advanced auditory scene analysis and stream segregation (Williges et al., 2019). The amplified input originating from the poorer ear provides the auditory cortex with the spatial context of the masking noise, allowing it to apply complex binaural squelch mechanisms to suppress the noise centrally (Williges et al., 2019).

Speech identification scores did not significantly improve when the masker was directed towards the better ear (S0NB)

When the target words were presented from the front, and the multi-talker babble noise was directed to the better ear, there was no significant improvement in the SIS. This finding contradicts studies by Bishop et al. (2017) & Williges et al. (2019), which report that when noise was presented to the better ear, performance significantly improved in the aided condition.

In the unaided condition, during the presentation of target words from the front and the multi-talker babble noise towards the better ear, the auditory system is forced into an informational masking situation. The better ear is completely loaded with multitalker babble information and is unable to extract the target words. And because of the severe loss in the poorer ear, it is unable to separate the target and babble noise, the unaided absolute SIS further decreases in the better ear condition (Bishop et al., 2017).

Again, in the aided condition, Bishop et al. (2017) demonstrated that when noise was directed to the better ear and speech to the poorer ear, SNR loss decreased and word recognition increased in the aided condition, as the hearing aid amplifies speech arriving at the poorer ear and the head shadow effect dampens the noise reaching the hearing aid microphone.

Also, Williges et al. (2019) noted that in bimodal users, when aided with a hearing aid only in the poorer ear and noise directed to the better ear, the SRT decreased and speech identification increased. The researchers reasoned that the improvement was due to the 'selective better ear listening strategy', i.e., when the noise was directed to the better ear, the participants directed their attention to the poorer ear, where the hearing aid gave better information about the target signal. Here, the poorer ear became the 'better ear' temporarily for this condition due to the head shadow effect (Williges et al., 2019).

But in contradiction, in our study, the better ear is still loaded with the masked information, and the head shadow attenuates the high-frequency information or the ILD cues of the target words. Here, the head shadow advantage, which helped in poorer ear condition, plays an antagonist role when it comes to the better ear condition. Thus, there was only a marginal increase in the absolute SIS in this condition, and the hearing aid benefit was still a question mark.

SRM did not improve in the aided condition compared to the unaided condition

Despite the raw improvements in SIS across the noise conditions, Spatial Release from Masking demonstrated no statistically significant differences between the unaided and aided conditions. This finding is consistent with Dawes et al.'s (2013) study, where they investigated SRM in 17 naïve unilateral hearing aid users with mild to moderate hearing loss using coordinate response measure (CRM) corpus stimuli and found a non-statistical improvement in the aided SRM between the spatial conditions (0^0 azimuth & both +/- 90° azimuth).

Similarly, the finding is consistent with Bishop et al. (2017) study, in which they found that spatial release of masking was not significant when the speech was directed to the better ear and noise was directed to the poorer ear (180^0 to each other).

The reason for SRM to decrease, even when the audibility is restored, is that poor spectral and temporal resolution occurs when both hearing thresholds increase and the residual hearing decreases in the aided ear (Dawes et al., 2013; Bishop et al., 2017; Williges et al., 2015; Williges et al., 2019).

In contradiction to the study, Bishop et al. (2017) found that the SRM improved significantly, with speech and noise spatial separation of 180^0, when the speech was directed to the worse ear and the noise was directed towards the better ear. This might be due to the restoration of audibility in the poorer ear and suppression of the noise that was directed to the better ear, due to the head shadow effect that naturally attenuates the competing noise before it could reach the hearing aid microphone.

Furthermore, the current data exhibited widespread inter-subject variability. Advanced spatial research has well-documented this asymmetry in the population with asymmetric hearing loss. As reported by Ching et al. (2011) in a pediatric study, the natural head diffraction can increase the overall sound pressure level at the near ear by an average of up to 3 dB. A study by Williges et al. (2019) also showed intersubject variability within the actual speech recognition threshold compared to the controls.

This might be because the participant's damaged auditory system cannot successfully make use of Interaural Time Differences (ITDs) and Interaural Level Differences (ILDs) to suppress this suddenly amplified noise at the level of the brainstem; the increased noise at the aided ear only degrades the SNR, leading directly to a negative SRM calculation (Williges et al., 2019).

Digital hearing aids, which are good at restoring audibility through amplification. It often suffers from physical processing delays and spectral distortions (Keidser et al., 2006). In normal individuals, precise ITDs on the magnitude of microseconds (μs) are actively used by the superior olivary complex to localise low-frequency sounds and unmask speech from noise (Kanagokar et al., 2026). This processing delay of the digital BTE hearing aid distorts these highly precise ITD cues. Even though the amplified signal is presented to the poorer ear, there is a severe temporal mismatch, which prevents the true binaural squelch and binaural performance (Keidser et al., 2006; Bogaert et al., 2006). This limitation of the hearing aid might explain the no significant improvement in spatial release from masking.

Other factors: Informational Masking, Cognitive Load, and Linguistic Context

In the current study, the effect of informational masking and cognitive load was not examined. The central nervous system, attempting to integrate the two incoming auditory streams, is suddenly confronted with a high-fidelity noisy signal from the better ear and a heavily distorted, temporally delayed, and amplified noisy signal from the poorer ear (Richter et al., 2024). The intense cognitive effort required by the brain to suppress the degraded input from the aided ear likely exhausts the cognitive resources necessary for the central unmasking process, thereby shrinking the overall spatial release from masking (Williges et al., 2019). This aligns tightly with the broader audiological literature, indicating that non-surgical contralateral routing of signals (CROS) devices and bone-anchored hearing aids (BAHA) can sometimes produce similarly deleterious effects when noise is presented directly to the better ear, as they funnel noise into the only functioning auditory pathway (Heyning et al., 2016b).

The multi-talker babble masker introduces an exceptionally high degree of informational masking into the testing paradigm (Suveg et al., 2025). Unlike steady-state speech-shaped noise (SSN), which primarily induces energetic masking by merely physically overlapping the target frequencies at the basilar membrane, multi-talker babble competes fiercely at the advanced cognitive and linguistic levels (Jain et al., 2025). It severely taxes working memory and higher-order executive function, as the listener must actively and continuously suppress intelligible background speech patterns while simultaneously isolating the target linguistics (Basavanahalli & Kumar, 2021).

Chapter 6

Summary and Conclusion

Single-Sided Deafness (SSD) leads to a severe to profound hearing loss. These individuals perform poorly on speech perception in noise. This is primarily because of disruption in the binaural mechanisms of the central auditory system. Thus, SSD may affect the Spatial Release from Masking (SRM), which affects the real-world listening environments.

The study aimed to evaluate the efficacy of a digital hearing aid (Danavox Klar 498 DW SP BTE) in restoring Spatial Release from Masking (SRM) among 11 adult patients diagnosed with SSD who were native Kannada speakers. The study employed a repeated-measure within-subject experimental design. Participants were required to identify phonemically balanced Kannada words in the presence of four-talker babble noise. Three spatial configurations were used. S0N0 noise condition, where target speech and noise were co-located at the front, whereas S0NB and S0NP conditions target speech at the front & noise directed to the better ear and the poorer ear, respectively.

The amplification to the poorer ear resulted in statistically significant improvements in absolute speech identification scores (SIS) in both the co-located condition (S0N0) and the condition where noise was directed at the poorer ear (S0NP), but there was no significant difference in the condition when noise was directed at the better ear (S0NB). Further, the spatial release from masking for better and poorer ears showed no significant difference in aided and unaided conditions.

The key findings of the study are as follows:

- Overall, participants demonstrated better speech identification performance in the aided condition relative to the unaided condition across all noise conditions.

- In the aided condition, SIS improved across all listening conditions compared to the unaided condition. The highest mean SIS was observed in the S0NP condition, followed by S0NB and S0N0.
- In the S0N0 condition, a statistically significant difference between the aided condition and unaided scores [t (10) = 3.96, p = .003, d = 1.03]. This was possibly due to the restoration of the audibility, binaural summation and integration
- In the S0NP condition, a statistically significant improvement was observed between the aided and the unaided scores [t (10) = 3.16, p = .010, d = 0.716]. This was possible because the amplified signal helped in identifying the spatial context of the noise and suppressing it by the mechanism of binaural squelch.
- In the S0NB condition, there was no statistically significant improvement in the aided scores compared to unaided scores [t (10) = 1.617, p = .137, d = 0.203]. This could be because of informational masking and the negative impact of the head shadow effect.
- SRM has not shown improvement in aided condition for both better ear and poorer ear. There was no statistically significant difference between the aided scores for better ear (Z = 1.44, p = 0.17) and poorer ear (Z = 0.36, p = .76) due to the absence of essential ILD cues to overcome binaural interference.

Conclusion

Though a hearing aid could not provide true spatial release of masking, it could actually improve the identification of the target words when both target signal and babble are collocated by restoring audibility or when the words are presented towards the front and babble from the poorer ear via binaural integration and redundancy. Also, the amplified input originating from the poorer ear provides the auditory cortex with the spatial context of the masking noise, allowing it to apply complex binaural squelch mechanisms to suppress the noise centrally.

Implication

- The current study can serve as a basis to counsel the benefits of hearing aid use in single-sided deafness patients.
- It can be taken as a foundation for creating training modules for identifying target words in a babble condition, from different speaker locations.

Limitations

- Relatively small sample size (*N* = 11) limits the broad statistical power.
- The gender of the sample was not equally matched. Hence, the gender effect could not be studied.
- As children, adolescents or the geriatric population were not recruited in the study, the effect of age could not be analysed.
- Furthermore, the strictly cross-sectional immediate experimental design explicitly does not account for the vital phenomenon of auditory acclimatisation (Megha & Maruthy, 2020).

Future directions

- Longitudinal studies have consistently shown that central binaural integration & sound localisation abilities continue to mature and refine over 6 to 12 months following the permanent introduction of a rehabilitative device in SSD cohorts (Kumpik & King, 2019).
- Outcomes at different speaker locations other than 0^0 azimuth, or +/- 60° azimuth, can be incorporated.
- The effect of other rehabilitation devices, such as CROS, BAHA or CI, on the spatial release of masking in single-sided deafness can be investigated.

- Participants with single-sided deafness of different native languages can be studied.
- Children with single-sided deafness can be included in the study to analyse the age effect for spatial release of masking.
- Training modules for improving identification of target words in a babble condition, from different speaker locations.

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Annexure I – Document of ethical clearance

All India Institute of Speech and Hearing
(An autonomous Institute under the
Ministry of Health and Family Welfare, Govt. of India)
Center of Excellence - Assessed & Accredited by NAAC with 'A' Grade
ISO 9001.2015 Implemented Institute
Manasagangothri, Mysuru-570006

ಅಖಿಲ ಭಾರತ ವಾಕ್ ಮತ್ತು ಶ್ರವಣ ಸಂಸ್ಥೆ
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मानसगंगोत्री, मैसूरु - 570 006

INSTITUTE REVIEW BOARD (IRB) APPROVAL FOR BIO-BEHAVIOURAL RESEARCH PROPOSAL INVOLVING HUMAN SUBJECTS AT AIISH

AIISH Institute Review Board (IRB)

Ref: SH/IRB/M.4/AUD.36/2025-26 **Date: 06.01.2026**

Title of the Dissertation	: Effect of Hearing Aid Use on Spatial Release from Masking in Individuals with Single-Sided Deafness
Name of the Investigator	: Bharath Pandian P.
Guide	: Mrs. Sahana P.
Co-Guide (if any)	: --
Proposed Duration of the Project	: 08 months
Source of funding	: Non-funded Master's dissertation
Estimated budget	: Nil
Reference Number of the Project	: Nil
Date on which the IRB meeting was held	: 02.01.2026

A clear statement of the decision reached IRB meeting (In the vent of the proposal is not approved, a statement of reasons for the same must be indicated) : **APPROVED**

Advice & suggestions (if any) : NIL

Signature & Name of the Member Secretary-IRB
Dr. Animesh Barman
Professor of Audiology
All India Institute of Speech and Hearing, Mysore-570006

सदस्य सचिव / Member Secretary
Institutional Review Board
अखिल भारतीय वाक् श्रवण संस्थान
All India Institute of Speech and Hearing
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