The Effect of Varying the Inter-stimulus Interval on Auditory Stream Segregation in Individuals with Normal Hearing and Cochlear Hearing Loss

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CERTIFICATE

This is to certify that this dissertation entitled **‘The Effect of Varying the Inter-stimulus Interval on Auditory Stream Segregation in Individuals with Normal Hearing and Cochlear Hearing Loss’** is a bonafide work submitted in part fulfilment for degree of Master of Science (Audiology) of the student Registration Number: P01II21S0084. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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CERTIFICATE

This is to certify that this dissertation entitled **‘The Effect of Varying the Inter-stimulus Interval on Auditory Stream Segregation in Individuals with Normal Hearing and Cochlear Hearing Loss’** has been prepared under my supervision and guidance. It is also been 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 **'The Effect of Varying the Inter-stimulus Interval on Auditory Stream Segregation in Individuals with Normal Hearing and Cochlear Hearing Loss'** is the result of my own study under the guidance a faculty at 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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ABSTRACT

Background: The present study investigates the impact of cochlear damage on auditory fusion and fission thresholds, particularly focusing on changes in the Inter-Stimulus Interval (ISI) of input signals in auditory stream segregation. The research employs the ABA with F_0 discrimination paradigm to measure these thresholds in both normal-hearing and pathological cochlea-affected adults. Fusion and fission thresholds play a crucial role in integrating or segregating sounds, enhancing communication in challenging listening conditions, particularly concerning individuals with hearing loss. While previous studies have explored the effects of cochlear damage on spectral aspects, this research delves into temporal processing, filling a gap in our understanding of auditory processing abilities in pathological groups.

Method: Thirty adults subjects, divided into two groups, participated in the study. Group I consisted of individuals with normal hearing and Group II with cochlear hearing loss. ABA with F_0 discrimination paradigm assessed fission and fusion thresholds. The F_0 between A and B was varied in semitones. In fission, the subjects listened to the sequence of sounds occurring rapidly, and perceived them as hearing more than one stream. If they perceived it as a single stream, it led to fusion percept. The responses were recorded for ten ISIs (from 10 to 100 ms in 10 ms steps).

Results: The fusion and fission thresholds obtained for individuals with normal hearing and those with hearing loss were compared within groups across ISIs and between the groups. The fusion and fission thresholds showed a significant within group effect, i.e., a significant effect of ISI on thresholds. There was also a significant effect of hearing loss across all ISI. Normal hearing individuals had better thresholds than individuals with hearing loss across all ISIs. The results showed that both hearing loss and ISI affect auditory stream segregation, indicating that along with the frequency, the temporal aspects are also affected in individuals with mild-moderate cochlear hearing loss.

Conclusion: The findings of this study show that individuals with hearing impairment have difficulties often with temporal processing along with impaired spectral resolution.

Keywords: *Auditory stream segregation, fusion thresholds, fission thresholds, Inter-stimulus intervals, galloping rhythm, streaming, temporal processing.*

Abbreviations:

CF - Characteristic frequency

ERB - Equivalent rectangular bandwidth scale

EEG - Electroencephalography

FB - Fission boundary

F_0 - Fundamental frequency

HI - Hearing impaired

ISI - Inter-stimulus intervals

MEG - Magnetoencephalography

MCLs - Most comfortable loudness levels

SD - Standard deviation

TCB - Temporal coherence boundary

UCL - Uncomfortable loudness levels

VTL - Vocal tract length

CHAPTER 1

INTRODUCTION

The ear tends to perceive signals depending on their acoustic characteristics when multiple auditory signals arrive simultaneously. When two signals appear to arise from a single source, they can be heard as a single stream, thereby leading to a fused percept. However, when sounds appear to arrive from different or separate sources, the sounds heard individually would be perceived as different, which is known as the perception of fission or segregation (Moore & Gockel, 2012). The most critical consequence of fusion and fission thresholds is seen in Cocktail Party situations (Cherry, 1953). It explains the difficulties listeners face when there are multiple sources of sound and the listener has to focus on just one stream to hear the speaker. While individuals with normal hearing can still resolve the information received from the speaker through normal peripheral hearing, it may be a challenge for individuals with hearing impairment. Fission and fusion help separate streams or integrate streams that depend on the task at hand. The literature review has shown that the differences in the frequency or temporal cues lead to fission percept (Grimault et al., 2002; Houtsma & Smurzynski, 1998; Iverson, 1995).

The inter-stimulus interval (ISI), i.e., the time difference between two signals, had shown variable effects on fission and fusion thresholds in individuals with normal hearing. Such an effect in individuals with cochlear hearing loss has yet to be investigated explicitly and is aimed in the present study.

Researchers have explicitly measured the effect of ISI on fission and fusion threshold in normal hearing individuals. They have found that stream segregation primarily occurs due to ISI differences between tones of the same frequency (Bregman et al., 2000). According to Grimault et al. (2002) and Vliegen et al. (1999), signals having more temporal distance were perceived as segregated. However, Spielmann et al. (2013) found that ISI alone did not affect fission thresholds. The difference in the findings might be due to the values of ISI used by different researchers. It was observed that with change in inter-stimulus intervals, fission was favoured at mid-ISI (500 – 100ms) compared to short (<50ms) and long (>100ms) ISI, with normal hearing subjects when measured across 10ms to 300ms (Simon & Winkler, 2018). Van Noorden (1975) explained a trade-off between frequency and ISI. At approximately 50 ms of ISI, the fusion occurred at a lesser difference in the frequency (Δf), and fission happened at the mid and high differences. As the ISI increased, it required more Δf for fission percept.

Earlier studies on the effect of cochlear damage on auditory stream segregation have manipulated the signal frequency (Rose & Moore, 1997), fundamental frequency of speech signal (David et al., 2018), modulation frequency (Antony & Barman, 2021) the pitch of the iterated rippled noise (Shearer et al., 2018), and spectral profile (Banerjee & Prabhu, 2021). Most researchers showed a significant reduction of fission and fusion thresholds attributed to decreased frequency selectivity due to cochlear damage.

Stainsby et al. (2004) stated that the broader auditory filter in cochlear damage might lead to deficits in streaming based on the temporal structure of the harmonic sounds. A sharply tuned auditory filter processes faster variation in frequency (fine structure) and slowly varying amplitude information (temporal envelope) together. Henry and Heinz (2016) stated that broader auditory filters decrease the phase-locking of the neural fibres. It leads to reduced temporal processing (Peterson & Heil, 2019). At the same time, Rose and Moore (1997) rejected the idea that cochlear frequency selectivity affects fission boundaries and later demonstrated that frequency discrimination thresholds are not related to fission boundaries (Rose & Moore, 2005). Valentine and Lentz (2008) indicated that listeners with normal hearing and hearing loss had the same stream segregation abilities for broadband inharmonic complex sounds. There are, however, earlier reports that despite poor phase locking, temporal processing is not markedly affected after cochlear damage (Harrison & Evans, 1979; Miller et al., 1997; Woolf et al., 1981). The present study has attempted to understand the effects of temporal processing on stream segregation in normal hearing and the hearing-impaired population.

1.1. Need for the study

The impact of cochlear damage on auditory fusion and fission thresholds, with changes in ISI of the input signals, in auditory stream segregation has not been investigated. The current study aims to address this need by measuring the effect of ISI using the ABA with F_0 discrimination paradigm to measure auditory fusion and fission thresholds in adults with normal and pathological cochlea.

The fusion and fission thresholds aid in integrating or segregating sounds, which helps subjects become effective communicators even in adverse listening situations. It has become a significant concern for individuals with hearing impairment. While the impact of cochlear damage on fusion and fission thresholds has been relatively studied under spectral aspects, the effect on temporal processing has not been studied exquisitely. The temporal processing abilities in cochlear hearing loss remain to be vague. Therefore, this study can also add to the literature and help understand the processing abilities of pathological groups.

1.2. Aim of the study

The present study aimed to measure the effect of ISI on auditory stream segregation (fusion and fission thresholds) in individuals with normal hearing and mild-moderate cochlear hearing loss using the ABA paradigm.

1.3. Objectives of the study

- To measure the fusion and fission thresholds across varying ISI in individuals with normal hearing and cochlear hearing loss.
- To compare the fusion and fission thresholds obtained at different ISI between individuals with normal hearing and cochlear hearing loss.

1.4. Hypotheses

The following null hypothesis will be tested in the proposed research.

- There will be no effect of different ISIs on fusion and fission thresholds in individuals across normal hearing and cochlear hearing loss.
- There will be no difference in fusion and fission thresholds obtained at different ISIs between individuals with normal hearing and hearing loss.

CHAPTER 2

REVIEW OF LITERATURE

The sounds and their components are naturally interleaved and overlapped in time. The separation of these sounds from their constituent parameters forms the phenomenon of auditory scene analysis (Bregman & McAdams, 1998). It is called so because the perceived sounds are continually grouped or separated as sensory data, making mental representations referred to as 'streams' (Bregman & McAdams, 1998). Perception of a group of sounds arriving one after the other or successively and/or simultaneously as a coherent whole, which seems to occur from one source, is called a stream (Bregman, 1990). For example, If a violin is being played, the source here would be the violin, and the stream would be the percept of the violin. While listening to a sequence of sounds occurring rapidly, the sounds can be perceived as hearing more than one stream (fission / segregated percept) or as a single stream (fusion / coherent/ integrated percept) (Bregman, 1990; Noorden, 1975). When listening to a mixture of sounds, it is this ability of the auditory system that aids in separating the dissimilar components and grouping of like components that help attend to the nature of that sound.

According to Bregman (1990), the separation process is data-driven, including pre-attentive auditory processes that are obligatory and automatic. This, in turn, functions to split the appearing sound waveform into more minor constituents and analyzes the acoustic features of the smaller parts. Likewise, grouping these sounds, which occur from a common source, can be represented perceptually as a coherent whole based on similar acoustic properties. On the other hand, schema-based scene analysis requires a higher level of cognitive input to perceptually group sounds. It can influence the listener's attention and prior expectations that may have occurred based on previous learning.

If two sounds of equal durations are presented, i.e., one of high frequency (H) and one of low frequency (L), and are alternated, a cycle of sounds is heard, repeating over time between the two tones. When the cycle begins slowly, e.g., three tones/second, listeners perceive an up-and-down pitch pattern with a rhythm containing all the tones. This is called a galloping rhythm. As the speed fastens, the galloping rhythm cannot be heard and is replaced by two streams of sound, one that contains all the H sounds, and another containing all the L sounds. This results in grouping the tones perceptually into two distinct streams (Noorden, 1975). When the speed is neither too fast nor too slow, i.e., intermittent, it results in ambiguous percepts where the listeners themselves can consciously control whether one or two streams are heard (Bregman, 1990). In slower conditions, a galloping rhythm is usually heard because the perceptual distance or the temporal separation between H and L tones: '*d'* is lesser than the distance between subsequent similar tones. Therefore, the sounds neighboring to the tones (HLH) will form one stream. However, as speed increases, the distance '*d'* between H and L tones will increase while the distance between subsequent similar tones reduces, thereby grouping all the like tones into one stream and the remaining into another (HHH, LLL). In this case, two streams will be formed, one with all high sounds and the second with all the low sounds. This signifies the importance of temporal distance between two sounds.

The points where the percept can change from one coherent stream to two streams or vice versa can be applied to measure a critical value. Two streams are perceived when the separation of two tones in terms of frequencies is more significant than one critical value. This point is the temporal coherence boundary (TCB) or fusion boundary (Beauvois & Meddis, 1996; Noorden, 1975). If the frequency separation is lesser than another critical value, it results in the perception of a single stream which forms that fission or stream segregation boundary (Beauvois & Meddis, 1996; Noorden, 1975).

Fission can occur at any point in time. If the frequency separation is very high, fission can be perceived at the beginning itself, and as the separation decreases, the onset of fission can also vary and may be heard towards the end of the stimulus. When a sound sequence of a longer duration is presented with a difference that is intermediate to the sounds present, the likelihood of stream segregation increases with increasing listening time to the tone sequence. Grouping by pitch produces segregated sub-streams and as exposure time increases, the auditory system starts to get adapted. It could be because the auditory system primitively assumes that there would be a single source of sound, this source gradually weakens the single stream causing perception of two streams when there is sufficient evidence to build up a contradiction to this assumption. Adaptation can reflect an accelerating decline of information presented with respect to the temporal order. It can cause a loss of time information which can alter the perceptual distance '*d*' between two tones. Therefore, a trade-off between time and pitch proximity is evident, ultimately resulting in favor of fission (Anstis & Saida, 1985). It was observed that with increase in tone repetition time, the temporal coherence boundary increases markedly, while fission boundary gets mildly affected by the same (Noorden, 1975).

There are various theories, which have been proposed to explain auditory stream segregation. Three of the most commonly accepted theories are as follows:

1. Bregman's theory: Bregman (1990) proposed a theory which focuses on streaming of alternating frequency sequences. According to this theory, auditory stream segregation occurs based on specific gestalt grouping principles. There are two main ways of grouping the processes: simultaneous (additive of all concurrent sounds, all heard simultaneously, like hearing several pure tones co-occurring resulting in a complex sound) and sequential (sounds are grouped over time, which causes interlinking of tones resulting in a melody). The tendency to segregate and cause streaming builds up over a period of several seconds. As the tones stop, the ability to perceive two tones gradually decreases.
2. vanNoorden's Theory: vanNoorden (1975) suggested that tone sequences, when alternated, can activate pitch-motion (frequency jump) detectors. These detectors further get adapted, and the capability to follow the galloping rhythm diminished. Anstis and Saida (1985) reported results consistent with Noorden's hypothesis (1975). The adaptation process occurs mainly at the frequency region of the alternating tones. This process gradually increases with time and tends to stay the same. Therefore, after splitting the stream of sounds, it does not return to the initial form of a coherent stream.
3. A theory by Jones (1976), suggested that the brain uses templates or neural representations of specific acoustic features, such as harmonics or fundamental frequencies, to segregate auditory streams. When the auditory input matches these templates, sounds are grouped; when there is a lack of match, they are perceived as separate streams.

Auditory stream segregation is intertwined with auditory spectral resolution. The accuracy of stream segregation is influenced by the ability of the auditory system to differentiate streams, i.e., fine resolution tends to enhance the ability to detect the minimum frequency differences between different streams. The property of the auditory system to differentiate the frequency components present in a complex signal, such as speech or music, is referred to as spectral resolution (Moore, 1995a). The auditory filters reflect the frequency selectivity of the cochlea. The basilar membrane in the cochlea of the inner ear can be viewed as a series of bandpass filters. Due to the basilar membrane's tonotopic property, the incoming signal's frequency provides maximum excitation in a specific membrane region, resonating with the stimuli. The width of the critical bands or auditory filters varies from base to apex, with them being wider at the apex and gradually narrowing towards the base. A narrow and stiff membrane at the base resonates more for high-frequency sounds, whereas a broader and more flexible membrane at the apex processes low-frequency sounds. According to Fletcher (1940), the basilar membrane pertains to a continuum of bandpass filters, each with a center frequency. These bands are proved to be wider at the apex and narrower towards the base. The ability to discriminate between sounds occurs only if their frequency separation is greater than the critical bandwidth. Sounds within the same bandwidth, cannot be resolved into their constituents. As the critical bandwidth is narrower at the apex, more sounds are likely to fall in different bands, yielding better frequency resolution at the lower frequencies.

Patients with cochlear hearing loss commonly complain of decreased ability to follow conversations in the presence of background noise. This difficulty may occur as some parts of the stimuli can fall below the subject’s absolute threshold attributing it to reduced audibility. However, there can be some difficulty even when sounds are amplified to equate to audibility (Moore, 1985). This effect can sometimes be explained as a sequel of impaired frequency selectivity observed in many patients with damage to the cochlea (Glasberg & Moore, 1986; Moore, 1995b). Patients with cochlear damage have broader auditory filters, which can lead to an increased predisposition to masking due to the interference of sounds and a reduced ability to discriminate variations of spectral shape in stimuli (Darwin, 2008).

Various authors have studied the effect of cochlear pathology by measuring the fission and fusion boundaries. Moore (1985), stated that the decreased temporal resolution and frequency selectivity which are typically found in patients with cochlear pathologies, prove to be a major cause of difficulties experienced in understanding speech, especially in noise background/ situations. Cochlear pathologies can result in changes in the frequency-to-place mapping within the cochlea. When there is outer hair cell dysfunction, that region's characteristic frequency (CF) decreases with increasing hearing loss. Following this, the place of peak excitation produced by a tone of a particular frequency shifts towards the basal end of the cochlea. If hearing loss is uniform across frequencies, all the CFs may shift towards the high frequencies by a similar proportion. In such cases, the fission boundary may show typical or near-normal values across frequency. However, when there are different configurations of hearing loss, and especially with variation in the amount of outer hair cell damage across frequency, the frequency-to-place mapping can be distorted in form (Rose & Moore, 1997). Many studies on auditory stream segregation have focused on the effects of stimulus parameters that can be manipulated and task demands on the streaming tendencies of normal-hearing listeners. Fewer studies have addressed the effects of such parameters on hard-of-hearing listeners.

Rose and Moore (1997) studied listeners with unilateral or bilateral cochlear hearing loss and normal hearing subjects and reported tonal stream segregation results. However, the results given in auditory filter bandwidth units and employed the equivalent rectangular bandwidth scale (ERBs) were mixed. It was observed that the normal and the unilateral hearing loss cases did not have much significant difference in streaming for stimuli of different frequency regions, which they mention can be due to compensation from the better ear. Bilateral hearing-impaired listeners, however, showed abnormal ERB differences. While the research did not strongly show a link between filter bandwidth and stream segregation, some other researchers thought that people with hearing loss might have trouble separating different sounds in repeating patterns. This could be due to their cochlea needing to improve at picking out specific frequencies in complex sounds (Grimault et al., 2001).

According to Wright (1968), temporal processing by the auditory system is also markedly affected by physiological disturbances at the level of the cochlea. Stainsby et al. (2004) stated that the broader filters in hearing-impaired listeners might lead to deficits in streaming based on the temporal structure of the harmonic sounds. A sharply tuned auditory filter processes faster variation in frequency (fine structure) and slowly varying amplitude information (temporal envelope) together. Henry and Heinz (2016) stated that broader auditory filters can reduce the neural fibers' phase-locking, which leads to reduced temporal processing (Peterson & Heil, 2019). A study by Valentine and Lentz (2008) indicated that listeners with normal hearing and hearing impairment had the same stream segregation abilities for broadband inharmonic complex sounds. A study done by (Shearer et al., 2018) also revealed that hearing-impaired listeners were less likely to perceive iterated ripple noise sequences as segregated compared to normal-hearing listeners, attributing to less pitch clarity or pitch strength in HI listeners.

For pure tone sequences, the frequency separation of subsequent tones significantly influences stream segregation. This is consistent with Beauvois and Meddis' theory (1996). This theory focused on the role of the temporal properties of auditory signals. Beauvois and Meddis' stated that temporal processing is important in segregating complex auditory scenes into distinct perceptual streams. The theory emphasizes the importance of neural firing patterns and temporal coherence in determining whether auditory components are segregated or integrated. However, the authors claim that pitch similarity on subsequent tones is still a critical factor despite the temporal process. For pure tones, frequency and pitch are inextricably linked. However, several earlier studies suggest that spectral similarity plays an important role compared to similarity in pitch (Moore & Gockel, 2002). Therefore, there are reports that despite poor phase locking, temporal processing is not markedly affected after cochlear damage (Harrison & Evans, 1979; Miller et al., 1997; Woolf et al., 1981). Although changing frequency is one of the significant factors that can affect segregation, many other factors may influence the streaming processes.

Factors that determine stream segregation:

1. Peripheral channeling:

The cochlea contains multiple overlapping bandpass filters for spectral analysis of incoming sound. These filters generate excitation patterns, representing the filters' output magnitude at their center frequencies (Moore & Glasberg, 1983). Research suggests that significant overlap in these excitation patterns caused by consecutive sounds leads to the perception of merged auditory streams (fusion), while minimal overlap tends to result in the perception of separate streams (fission) (Beauvois & Meddis, 1996; McCabe & Denham, 1997). Van Noorden (1975) experimented on normal-hearing listeners wherein two stimuli were presented. One stimulus was a pure tone, alternating with a complex tone with the same fundamental frequency (F_0), and the second one had two complex tones with harmonics in other frequency regions, while F_0 was kept constant. In both conditions listeners, always perceived two streams. The researcher concluded that contiguity "at the level of hair cells of cochlea" was a mandate condition for the occurrence of fusion.

Hartmann and Johnson (1991) studied streaming using melodies that were interleaved. The stimulus itself was generated such that it was difficult to recognize unless stream/stream segregation discrimination occurred. The stimuli were presented to the listeners in several conditions, including variations in temporal envelope, spectral composition, ear of presentation, and interaural time delay. Results showed that conditions where the tones differed in the spectrum or the ear change led to the best performance. Undoubtedly, most peripheral channeling was expected in these conditions. This confirmed that "peripheral channeling is of utmost importance" in determining stream segregation.

It is expected that due to reduced frequency resolution, or peripheral channeling, the individuals with hearing loss must have affected stream segregation. Banerjee and Prabhu (2021) reported poor auditory stream segregation thresholds for 21 ears with cochlear pathology. They attributed the poorer thresholds to the affected spectral resolution in cochlear pathology. Moore, (2002) also stated that the abnormalities in stream segregation associated with cochlear hearing loss may be a side effect of reduced frequency selectivity. However, it is unclear to what extent these difficulties are dominated by direct interference, i.e., by simultaneous masking, or by the failure of the mechanism of stream segregation. David et al. (2018) studied how individuals with hearing impairment perform speech sound segregation tasks. The stimuli were CV tokens alternated based on F_0 and/or simulated vocal tract length (VTL) differences.

Participants had to determine whether a "word" made up of two random tokens was present in the subsequent alternating sequences. They found that the individuals with mild and moderate cochlear loss could use F_0 and VTL difference cues to segregate the alternating sequences. Their results suggested that HI individuals do not necessarily have reduced stream segregation skills. Thus, there may be some factors other than peripheral channeling, which might have contributed to affected stream segregation, as reported by other researchers.

2. Phase spectrum:

The phase spectrum has been studied by using a stimulus that encompasses unresolved harmonics of a particular F_0. The stimuli were changed in terms of phase. Similar to the ABA paradigm, the testing was done by changing to a cosine or using a random alternating phase as B, while the A remained unchanged. Even with differences in phase spectrum, obligatory or primitive stream segregation for sounds having identical power spectra was observed (Bregman & McAdams, 1994; Cusack & Roberts, 1999). The effects of phase were presumably mediated by changing the waveform or envelope of the sound produced by using phase shifts (Roberts et al., 2002).

3. Fundamental frequency:

Bregman et al. (1990); Singh(1987) utilized tone sequences in which successive tones were made to vary in either spectral envelope, F_0, or both. Their findings indicated that F_0 and spectral shape could independently affect distinct streams' perception. However, their experiments employed tones made up of only resolved harmonics, so there was a possibility that changes influenced F_0 s impact in the excitation location of individual harmonics (Vliegen & Oxenham, 1999) employed sequences of complex tones having high tones of unresolved harmonics and varying F_0 differences between successive tones while maintaining the same spectral envelope across. This yielded excitation patterns of consecutive tones being quite similar. When the listeners were asked to judge segregation subjectively, they separated the tone sequences based on F_0 differences (possibly conveyed solely by temporal information), and their segregation judgments aligned with sequences of pure tones. This contrasts a similar experiment by Grimault et al. (2000), indicating that stream segregation based on F_0 differences between successive tones was more pronounced for complex tones having resolved harmonics than for tones with unresolved harmonics. The potency of a given factor in producing stream segregation may be related to the perceptual salience of changes produced by manipulating that factor (Moore & Gockel, 2002).

Generally, when segregation is beneficial, frequency differences alone can be as influential as spectral differences in encouraging stream segregation. However, F_0 differences are less potent than spectral differences in compelling obligatory segregation, which is advantageous in fusion scenarios (Moore & Gockel, 2012).

4. Attention:

Carlyon et al. (2003) presented a stimulus of long duration of tone sequence and reported the effect of attention and cognitive load on streaming. Subjects were asked to count backward in threes, which consequently involved considerable cognitive load. A 10-second interval was used, after which subjects were told to judge whether the tone had one or two streams. The stream segregation was found to have higher thresholds with a distracting task than without another task in the first 10 seconds. It shows the importance of attention. It was further observed that the build-up of segregation can be disintegrated either by not attending to stimuli or by switching attention, or both (Stainsby et al., 2004; Thompson, 2004).

Fuglsang et al., (2020) investigated the effect of hearing loss on simultaneous streaming during selective attention tasks. HI listeners performed well in a selective attention task involving two simultaneous speech streams. The HI listeners, in fact, showed enhanced EEG responses in low-frequency ranges for both attended speech and slow-paced tone sequences during passive listening. Both groups showed reduced responses to the ignored speech stream. However, the HI listeners rated the competing speech task as more challenging. The study suggests that speech comprehension issues in HI listeners might not necessarily stem from impaired attentional selection processes.

5. Temporal Envelop and Bandwidth:

Dannenbring and Bregman (1976), alternated between two sounds, using the ABAB paradigm in which the stimuli used for A and B included both pure tones or both narrowband noises or a tone combined with a narrowband noise. This was done to minimize the extent of peripheral channeling by keeping the noise bandwidth as less than one ERB to keep the excitation pattern of noise on par with that of a tone. The results indicated that the perceived segregation improved as the frequency difference between A and B increased. Despite this, segregation was also majorly observed for tone-noise combinations rather than tone-tone or noise-noise combinations. This occurred because, although the peripheral channeling seldom played a role, the temporal envelope became a salient cue. As the envelope of noise and that of tone were still different, there seemed to be a change in the quality/timbre of sounds, which the authors suspect led to segregation.

6. Interstimulus interval

Bregman et al. (2000) proposed that numerous factors could affect the ability of individuals to perceive fusion or fission, but two main factors that have been discussed have the most influence on streaming thresholds. These are known to be the inter-stimulus interval (ISI), and frequency separation (Δf). This temporal distance, or the distance in time between subsequent sounds, seems to be a salient feature. It was found that as the ISI was reduced, stream segregation improved. ISI within acts as an important time interval.

Noda et al., (2013) studied the neural mechanisms of auditory stream segregation with varying inter-tone intervals using rat models. The oscillatory phase modulation was researched as a potential neural correlate of auditory streaming. Earlier behavioural experiments have confirmed the rats' ability to organize auditory streams. Local field potentials were measured in the primary auditory cortex of anesthetized rats. The responses were measured in ABA sequences with varying inter-tone intervals and frequency differences. The results showed that higher-frequency bands correlated better with perceptual boundaries than local field potential amplitude. The responses were progressively increased within about 3 seconds from sequence onset. These findings showed the importance of temporal modulation of cortical oscillations, such as phase locking, in auditory stream perception, supplementing theories like forward suppression and tonotopic separation.

Fishman et al. (2004) studied the effect of ISI on stream segregation in a monkey's auditory cortex. Using the ABAB paradigm, tone interval was systematically varied and was presented to awake monkeys while neural activities were recorded in the primary auditory cortex. The findings suggest a physiological model of stream segregation whereby increasing ISI enhances spatial differentiation of tone responses along the tonotopic map in A1.

The ISI profoundly impacts auditory signal processing, and manipulation of the same can result in various aspects of perception. Varying ISI can help in auditory discrimination, integration, temporal resolution, and auditory stream segregation and is a commonly used procedure. Efforts have been made to vary the gap duration of such

ISIs to identify their effects on stream segregation on normal hearing and cochlear hearing loss.

Simon and Winkler (2018) systematically investigated the effect of ISI in normal-hearing adults. They measured fission thresholds using stimuli with different ISIs ranging from 10 ms to 300 ms. Their results showed elevated thresholds at short (<50 ms) and long (>100 ms) ISI than at mid-ISI (50-100 ms). Noorden (1975) also found that at approximately 50 ms of ISI, the fusion occurred at a lesser difference in the frequency (Δf), and fission happened at the mid and high differences. As the ISI increased, it required more Δf for fission percept. Beauvois (1998) used a high tone and a low tone interchangeably using a constant stimulus onset asynchrony of 130 msec having different frequency separations while varying the duration of the two tones separately or together (global duration). This revealed that stream segregation occurred more noticeably with a more significant global duration of the tone pair (Bregman et al., 2000) classified the durational aspects that can be manipulated as stimulus onset asynchrony: across the frequency range and within the same frequency range) and ISI (across and within). The results revealed that ISIs directly could influence segregation and mentioned that, although ISI–across is not a crucial factor, the ISI within is favorable to induce stream segregation. They found that an internal link could be assigned based on the onset of the sound and its build-up complimenting segregation. If the same sound is repeated, the link strengthens, and an integrated percept is formed. Consequently, if the sound is terminated, the link strength reduces. According to all three theories of segregation as discussed above, the ISI within holds good and is justifiable.

However, discrepant results have been obtained by Dannenbring and Bregman (1976), which implied that the listeners compensated for the increasing intervals by shortening the duration of tones linearly, whilst SOA was kept constant, proving that the duration of the stimulus was more fruitful. They reported that ISI per se did not provide additional contributions. However, results obtained by Vliegen et al. (1999a) suggest that though spectral information is dominant in inducing (involuntary) segregation, the periodicity information can also have a role. The information on the extent of the role of periodic information in streaming has been limited. Not many studies have shown the effect of varying the ISI in cochlear hearing loss.

Researchers (Grimault et al., 2000, 2002; Stainsby et al., 2004; Vliegen et al., 1999a; Vliegen & Oxenham, 1999) have demonstrated that in normal hearing population, any change in stimulus concerning its temporal structure, e.g., fundamental frequency differences for complex tones of unresolved harmonics, modulation rate differences, phase shifts can result in stream segregation. A review of studies related to streaming (Moore & Gockel, 2002) emphasizes that any significant salient perceptual difference between sounds can lead to the formation of streaming.

Thus, many factors affect auditory stream segregation in individuals with normal hearing and hearing loss. Although the studies particularly investigating the effect of these factors on stream segregation by individuals with hearing loss are limited, they have reported that streaming is affected due to hearing loss. Rose and Moore (1997) rejected the idea that cochlear frequency selectivity affects fission boundaries and later demonstrated that frequency discrimination thresholds are not related to fission boundaries (Rose & Moore, 2005). Valentine and Lentz (2008) indicated that listeners with normal hearing and hearing loss had the same stream segregation abilities for broadband inharmonic complex sounds. Stainsby et al. (2004) stated that the broader auditory filter in cochlear damage might lead to deficits in streaming based on the temporal structure of the harmonic sounds. A sharply tuned auditory filter processes faster variation in frequency (fine structure) and slowly varying amplitude information (temporal envelope) together. Henry and Heinz (2016) stated that broader auditory filters decrease the phase-locking of the neural fibers. It leads to reduced temporal processing (Peterson & Heil, 2019). There are, however, earlier reports that despite poor phase locking, temporal processing is not markedly affected after cochlear damage (Harrison & Evans, 1979; Miller et al., 1997; Woolf et al., 1981). The impact of cochlear damage on auditory fusion and fission thresholds, with changes in ISI of the input signals, has not been investigated. The current study aims to address this need by measuring the effect of ISI using the traditional ABA paradigm to measure auditory fusion and fission thresholds in adults with normal and pathological cochlea. Various authors have used many different experimental paradigms. The most often used paradigm is the ABA- paradigm, where it is easy for the subject to make out the galloping rhythm and segregate it into AA BB as per the instructions. The – indicates the silent interval. The paradigm depends according to the task at hand. If the task is to segregate, then using spectrally different stimuli can make it easier, i.e., if the task is to recognize two interleaved melodies, then the ones that make up the two melodies are heard as two streams. In contrast, it is difficult to perform tasks when the task is to segregate based on comparing the sounds concerning their timing characteristic in different streams.

In Noorden's (1975) experiment, a two-tone sequence was used, revealing ISI's effect. However, Dannenbring and Bregman's (1976) study used a four-tone repeating sequence, perhaps leading to no difference in ISI. When vowel sounds were used as stimuli, there was a pronounced effect of ISI (Thomas et al., 1971; Warren & Warren, 1970).

Stream segregation can be done subjectively, whereby subjects are asked if the perceived tones had one stream or two. This type of measure is advantageous due to its easy setup, with the availability to record the direct reports of the listeners. To measure the same objectively, the subjects can be asked to undergo a perceptual task, supported either by choosing an integrated or a segregated percept. A staircase procedure may be preferred to measure thresholds, which can be combined successfully with across-stream temporal judgments and used as a classical tool for measuring streaming. This ensures fast coverage, yielding a brisk assessment of streaming thresholds. While it was challenging to find both the thresholds using other methods and the range where it was ambiguous, the staircase method can not down the differences, which can further be used to interpolate with accuracy. Based on the task, three–down one-up, or a two–down one-up procedure may be used. In these procedures, if the subject does not perceive streaming, the difference between sounds increases in three / two steps, and if the response is correct, the task difficulty increases, and the difference between sounds further decreases in one step (Spielmann et al., 2013).

CHAPTER 3

METHODS

3.1 Research Design

Standard group comparison**.**

3.2 Subjects

Thirty subjects within the age range of 25-45 years were randomly selected for the study. The subjects were divided into two groups: Group 1 had individuals with normal hearing sensitivity (n = 15), and individuals with mild-moderate cochlear hearing loss (n = 15) were included in Group 2. The demographic details of the subjects are given in Table 1. The following inclusion and exclusion criteria was adopted for subject selection, as stated below.

3.2.1 The inclusion criteria for subjects of Group 1:

- All subjects who were native speakers of the Kannada language were chosen for the study.
- Pure tone hearing thresholds in both ears were less than ≤ 15 dB HL in octave frequencies from 250-8000 Hz ($\bar{X}$ = 7.5 dBHL for the Right ear; 7.33 dBHL for the Left ear). Audiometry was done using a calibrated audiometer (Piano, Inventis Inc., Italy) by following the modified Hughson-Westlake method for threshold estimation as per ANSI S3.21 (2009) specifications.
- Speech recognition thresholds (SRT) had ± 6 dB correlation with PTA (average threshold of 0.5, 1, 2, & 4 kHz), ($\bar{X}$ = 9.33 for the Right ear; 8.73 for Left ear). Speech identification scores (SIS) were greater than 90% for both ears. ($\bar{X}$ = 97.6% for the Right ear; 97.33% for Left ear). The SRT and SIS were measured

using standardized material following the procedure described by the American Speech-Language-Hearing Association (1988).

- The subjects who obtained amplitudes for otoacoustic emissions (OAE) at 6 dB above the noise floor at a minimum of three consecutive frequencies, in both ears, were chosen for the study. Transient evoked (TE) OAEs were measured using a calibrated OAE meter (ILOv6, Otodynamics Ltd, Hatfield, UK). All the subjects had OAE amplitudes present in the frequency range from 1 kHz to 4 kHz.
- All subjects had an ‘A’ type tympanogram and the presence of acoustic reflex in a minimum of 0.5, 1, and 2 kHz frequencies. The classification was done based on the Ear canal volume, Static compliance, Peak pressure, and type, based on the standard criterion (Feldman, 1976; Jerger, 1970; Lidén et al., 1974). Immittance testing was also done using a calibrated immittance meter (Titan, Interacoustics Inc., Denmark).

3.2.2 The exclusion criterion for subjects of Group 1:

- Subjects having a history of middle ear pathology within the last six months.
- Subjects with a history or complaint of neurological, psychological, behavioural, or systemic illness. Information regarding the above was obtained from the case history file and by an informal interview.
- Since all the subjects were native Kannada speakers, none of the subjects had difficulty understanding the instructions in Kannada. Opportunities were also given to the subjects to clarify if they had difficulty understanding a particular instruction. Despite clarification, if the subjects were having difficulty understanding instructions, they were excluded from the study.

- Subjects with a history or complaint of tinnitus, vertigo, or other auditory-vestibular problems were excluded during testing despite having normal pure tone thresholds. This was done because previous studies have shown that these problems can affect auditory processing abilities, which would have affected the results.

Based on the inclusion and exclusion criterion mentioned above, subjects on par with the criterion were chosen under group one, i.e., the normal hearing group.

3.2.3 The inclusion criteria for subjects of Group 2:

- All subjects who were native speakers of the Kannada language were chosen for the study.
- Pure tone thresholds (masked/unmasked) were within 26-55 dB HL, in octave frequencies. ($\bar{X}$ = 44.30 dBHL for the Right ear; 43.91 dBHL for the Left ear) with masked/unmasked air-bone gap ≤ 10 dB in both ears.
- Subjects with flat or gradually sloping audiogram configurations.
- SRT was ± 6 dB of PTA and SIS was greater than 80% ($\bar{X}$ = 46 for the Right ear; 46.33 for Left ear, SIS: $\bar{X}$ = 93.86 for the Right ear; $\bar{X}$ = 94.4 for the Left ear).
- Subjects who had absent/elevated TEOAE amplitude, with less than 6dB SNR, in three consecutive frequencies.
- All subjects had an ‘A’ type tympanogram and the elevated/absent acoustic reflexes in a minimum of 0.5, 1, and 2 kHz frequencies.

3.2.4 The Exclusion criterion for subjects of group 2:

- Despite giving multiple opportunities, the subjects who needed help understanding instructions without using an amplification device.
- The subjects having or perceived to have any progressive/ degenerative neurological conditions based on the previous case history reports and informal interviews.
- Subjects having sudden sensorineural hearing loss as reported by the participant's history and a provisional diagnosis of SSD given by ENT doctor and audiologist.
- Subjects with severe tinnitus affecting their auditory performances and ability to process information and concentrate for the duration of testing.
- Subjects with uncomfortable loudness levels less than 90 dB HL, as tested during the audiological evaluation, were excluded due to the involvement of recruitment in such cases.

Based on the above inclusion and exclusion criteria, all subjects were randomly selected from the audiology outpatient department of AIISH using a purposive sampling method. The subjects willing to volunteer for the study were requested to sign an informed consent form that complied with the study protocol used. Table 3.1 shows the demographic details and hearing and speech audiometry thresholds of the subjects of both groups. Figure 3.1 shows the mean audiometric thresholds across frequencies of subjects of both groups.

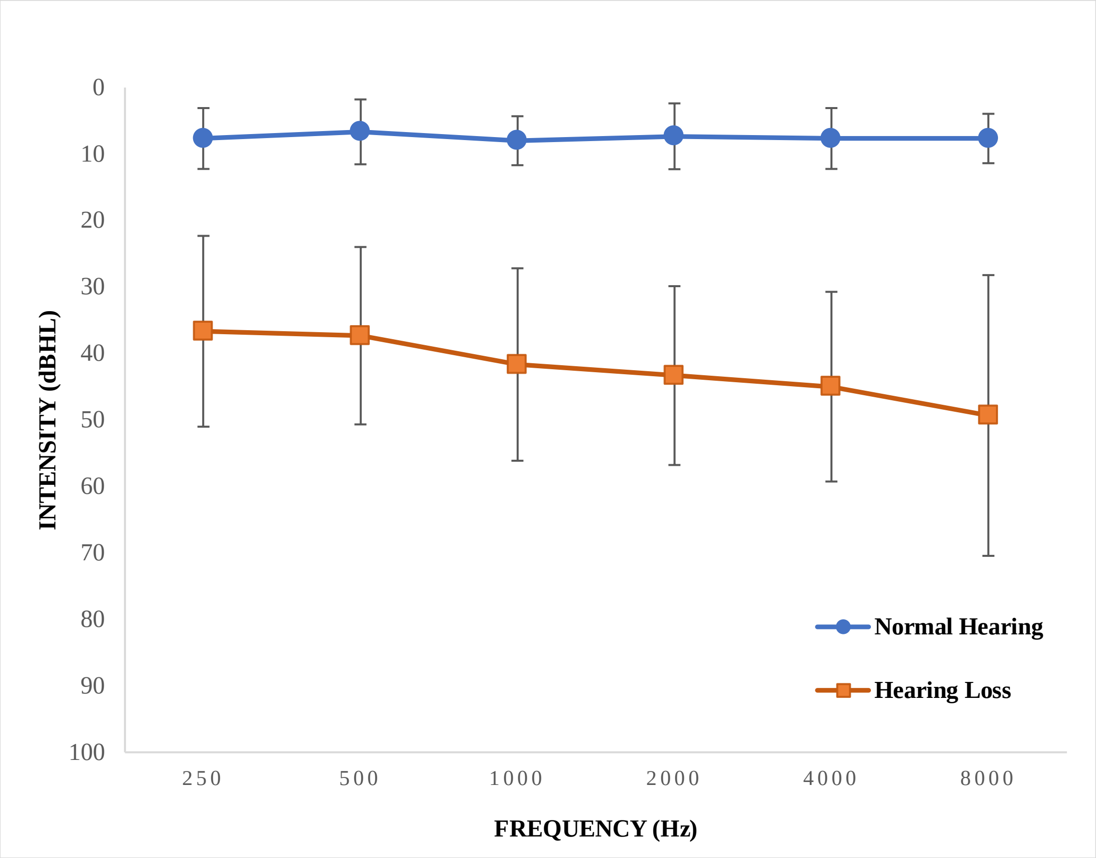
Table 3.1

The mean, SD, and range of hearing thresholds for individuals with normal hearing and hearing loss.

	Normal Hearing		Hearing Loss	
	Right Ear	Left Ear	Right Ear	Left Ear
No. of subjects	15 (8 females + 6 males)		15 (8 females + 7 males)	
Age (in years)				
Mean	31.00		38.4	
SD	3.38		6.56	
Range	25-36		25-45	
PTA (in dB HL)				
Mean	7.50	7.33	44.30	43.92
SD	3.60	2.67	11.65	12.71
Range	2.50-13.75	2.50-11.25	26.25-58.75	22.50-57.5
SRT (in dB HL)				
Mean	9.33	8.73	46.00	46.33
SD	3.71	2.89	12.71	12.32
Range	05-15	05-15	25-65	25-60
SIS (in %)				
Mean	97.60	97.33	93.87	94.40
SD	2.52	2.47	6.74	7.53
Range	92-100	92-100	80 – 100	80 – 100
MCL (in dB HL)				
Mean	46	45	77.67	78.67
SD	4.71	4.63	9.78	10.08
Range	40-55	35-55	60 – 90	60-90
UCL (in dB HL)	>100	>100	>90	>90

Figure 3.1

The pure tone audiometry thresholds across octave frequencies from 250 to 8000 Hz of subjects with normal hearing and hearing loss.



Note. The error bars represent the standard deviation.

3.3 Measurement of Fission and Fusion Thresholds

The fusion and fission thresholds were measured using the ABA paradigm. ABA sequences are widely used to assess auditory stream segregation and give consistent and repeatable results (Moore & Gockel, 2012). If the difference in the fundamental frequency (Δf) of the stimuli in A and B is more than a critical value, called the temporal coherence or fusion boundary (TCB), the subjects hear two streams, at least after a few stimuli presentations. If Δf is less than a different critical value, called the fission boundary (FB), subjects heard one stream, irrespective of the number of stimuli presented. In the situations where percept “flips” spontaneously from one to two streams and back, i.e., in the range between the FB and the TCB, the percept is called ambiguous. Due to a lack of consensus among researchers to measure TCB or FB for stream segregation (Beauvois & Meddis, 1996; Haywood & Roberts, 2011; Singh & Bregman, 1998), both have been measured in the present study.

3.3.1 Stimulus

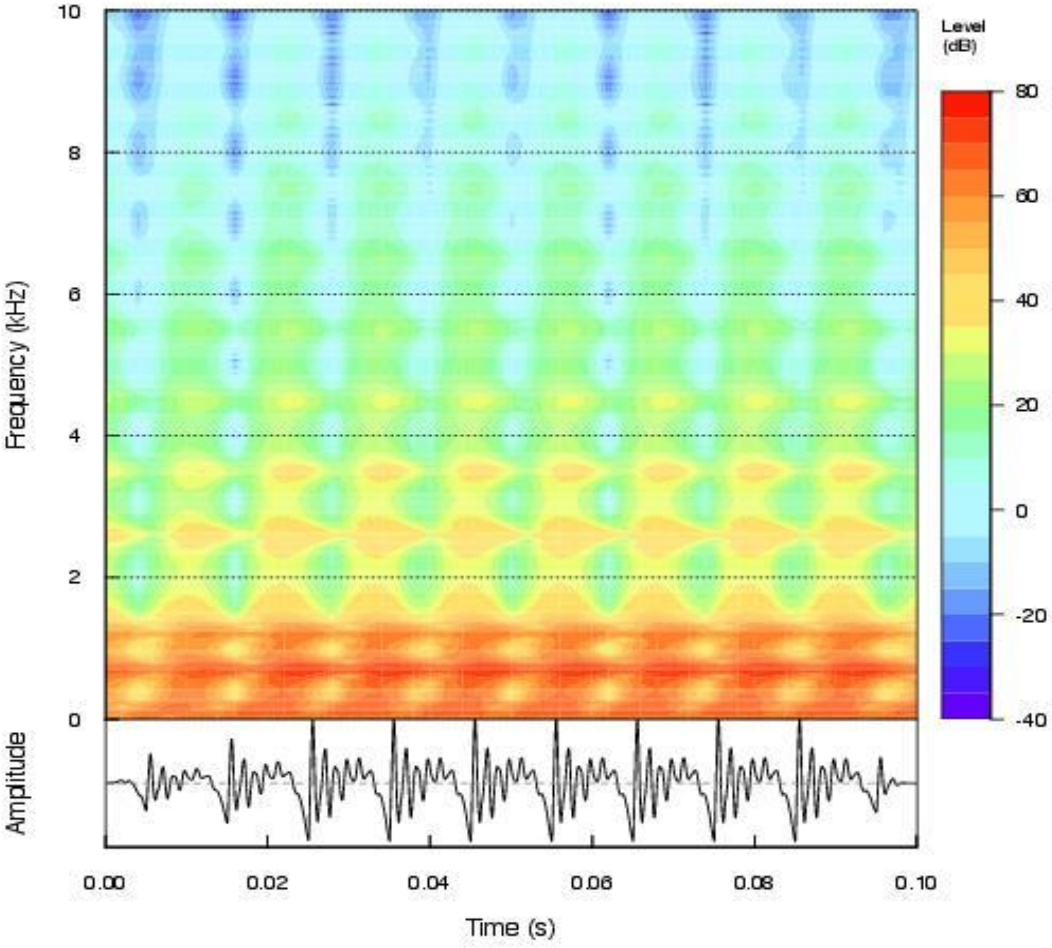
A synthesized vowel /ɑ/ was generated and used as a stimulus for testing. The stimulus was created using the Klatt synthesizer (Klatt, 1998) module of Matlab (v2016, 64-bit, sampling rate of 44100 Hz). Figure 2 shows the spectrogram of the synthesized vowel /ɑ/. The following acoustic parameters were selected for generating the vowel:

- F_0 = 100 Hz,
- F_1 = 700 Hz,
- B_1 = 130 Hz,
- F_2 = 1220 Hz,
- B_2 = 70 Hz,
- F_3 = 2600 Hz,
- B_3 = 160 Hz,
- Amplitude = *rms* normalized to 70 dB
- Duration = 100 ms with 10 ms raised cosine ramps at onset and offset.

F_0 denotes fundamental frequency, 'F' and 'B' indicate the formant frequencies and bandwidth, and the digits in the subscripts represent the number of formants.

Figure 3.2

Spectrogram and the waveform of the synthesized vowel /a/.



3.3.2 Stimuli Triplet

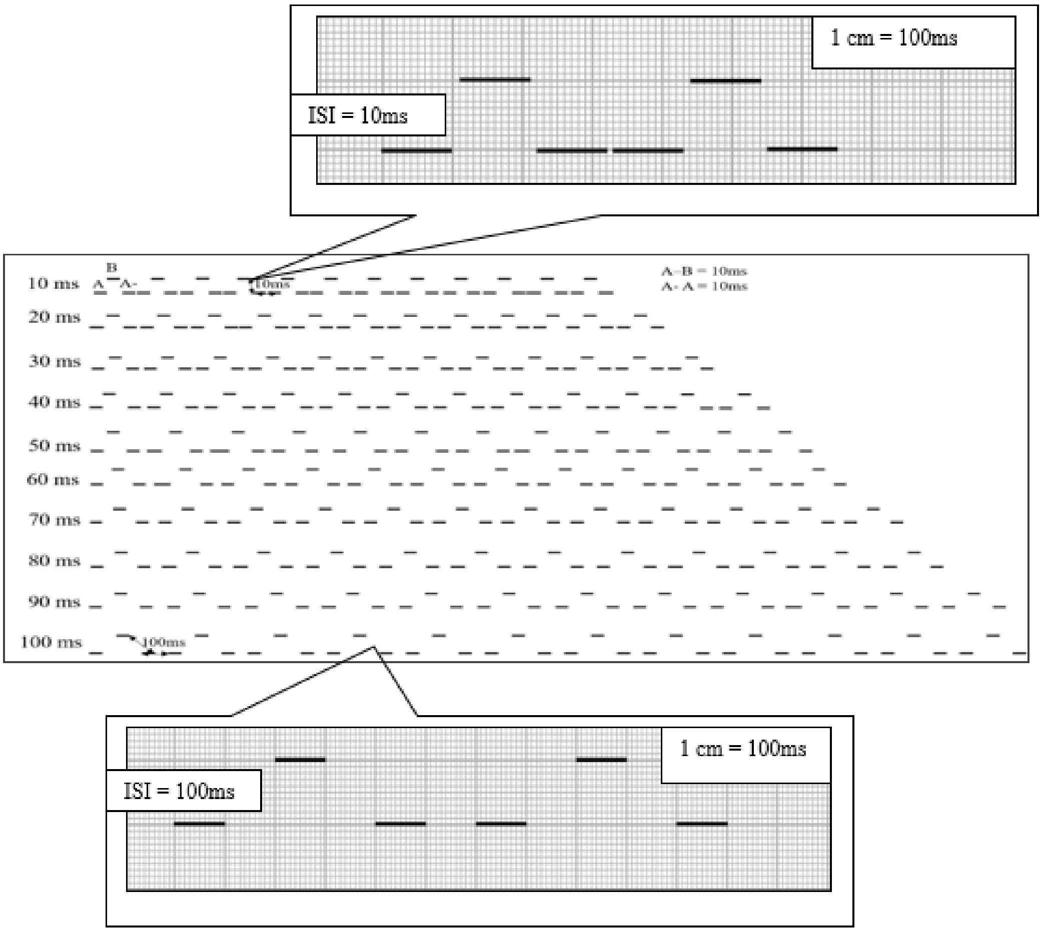
The vowel /ɑ/ was presented in a repeating ABA- sequence. The sequences 'A' and 'B' had the same vowel /ɑ/. Although the formant frequencies remained the same for successive stimuli, the fundamental frequency (F_0) differed between 'A' and 'B' (Gockel et al., 1999; Noorden, 1975). The '-' in the sequence indicates a silent interval. Vliegen and co-workers (Vliegen et al., 1999a; Vliegen & Oxenham, 1999) found that the F_0-based stream segregation paradigm is more complex than the centre frequency or spectral envelope-based paradigm. Thus, the F_0-based paradigm was used to make the task challenging to reveal subtle differences in auditory processing.

3.3.3 Stimuli Sequence

Twelve ABA triplets, played consecutively, formed the sequence for one trial. The intervals between the A and B vowels (ISI) used were 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 ms (values adopted from Simon & Winkler, 2018). Thus, ten sequences were created wherein, in each sequence, the ISI was kept the same within one sequence but varied across sequences. For example, in sequence 1, 10 ms ISI was kept constant, whereas in sequence 2, 20 ms ISI was constant. These values were used to measure the effect of short (10, 20, 30 ms), mid (40, 50, 60, 70 ms), and long ISIs (80, 90, 100 ms) on fusion and fission thresholds. The inter-triplet interval varied depending on the ISI, so the interval remains isochronous. The distance between 'A-A' and 'B-B' in an isochronous sequence remains the same. The representation of the stimulus is shown in Figure 3.3. The entire stimuli were generated using the signal processing toolbox of Matlab.

Figure 3.3

The arrangement of stimulus across ten sequences.



Note. The gap between the stimulus and the triplet increases with each sequence.

3.3.4 Procedure

The F_0 of ‘A’ was kept constant at 100 Hz, and the F_0 of ‘B’ was made to vary. The difference in F_0 has been denoted as Δf. The stimuli sequence was presented monaurally via a personal computer (equipped with an EVGA sound card) at each subject’s Most Comfortable Level (MCL) using the Sennheizer HD-206 headphones. The choice of the ear for stimulus presentation was kept random so that in 50% of the subjects, it was presented to the right ear, and in the remaining 50% of subjects, to the left ear. The output from the headphones was calibrated using a calibrated SLM meter and was set at the subject's MCL. A custom presentation platform was developed by adopting the staircase procedure in the Psychoacoustic Toolbox of Matlab.

3.3.5 Recording Responses

A computer number pad was given during testing, where the subjects were instructed to indicate by pressing the button labelled '0' if they hear one stream or stream with a galloping rhythm, '1' if the sound splits, and they hear two streams with a regular rhythm. The responses were recorded after each sequence presentation.

3.3.6 Scoring

If the subjects pressed ‘0’, the value of Δf increased, and Δf value decreased if the subject pressed ‘1’, on three consecutive trials. The Δf values ranged from 0-30 semitones, beginning with 15 semitones, and were adjusted in one-semitone steps using a two-down, one-up staircase procedure. The largest Δf value for which an integrated percept was reported was taken as fusion threshold. The smallest Δf value for which a segregated percept was registered was taken as the fission threshold (Bregman, 1990). This was obtained separately at each ISI. Thus, ten scores for fusion and fission for ten ISI values were recorded.

3.3.7 Practice Trials

Ten practice trials were given to familiarize subjects with the procedure. Triplets of maximum frequency separation, i.e., high- (4000 Hz) and low-frequency (250 Hz) bursts of pure tones as A and B, were played to check whether the subject could comprehend and attend to the procedure.

3.3.8 Response consistency

The fusion and fission thresholds were estimated using three complete adaptive runs at each ISI by measuring the Δf values, for 30% of subjects.

3.4 Test environment

Entire testing was done in a sound-treated double-room setup (ANSI, 2013) using calibrated instruments.

3.5 Statistical analysis

All the statistical analysis was carried out using the SPSS software.

- The test of normality was done using Shapiro-Wilk Normality Test
- To measure the consistency of fusion and fission thresholds, the Cronbach's alpha test was administered.
- The data that was normally distributed was subjected to repeated measures ANOVA to measure the effect of ISI and hearing loss on fusion and fission thresholds. Further, data obtained for normal hearing and individuals with hearing loss were compared using pairwise comparison with Bonferroni's corrections.
- The data that was non normally distributed was subjected to Friedman's test for within groups measures. Between group pairwise comparison was made using Mann-Whitney U test.

CHAPTER 4

RESULTS

The present study aimed to investigate the effect of varying ISI on auditory stream segregation by finding the fusion and fission thresholds in individuals with normal hearing and those with mild – moderate cochlear hearing loss. The data obtained included fusion and fission thresholds at ten inter-stimulus intervals (i.e., 10, 20, 30, 40, 50, 60, 70, 80, 90 ,100).

The response consistency of the thresholds obtained was analysed using the Cronbach's alpha test. The test was done for 30% of the subjects. The test showed that the response consistency was excellent. The scores obtained was 90.8% consistent across the two trials ($\alpha = 0.908$).

The data was analysed for normality using Shapiro-Wilk's normality test. The results for the thresholds of fusion followed normal distribution ($p > 0.05$), while the results for thresholds of fission did not follow the normal distribution ($p < 0.05$). Therefore, the data for fusion thresholds were subjected to parametric tests, while the fission thresholds, were analysed using non parametric tests.

The results obtained are discussed under the following subheadings:

4.1 The fusion and fission thresholds with varying ISI in individuals with normal hearing and cochlear hearing loss.

4.2 The fusion and fission thresholds at different ISIs between individuals with normal hearing and cochlear hearing loss.

4.1 The fusion and fission thresholds with varying ISI in individuals with normal hearing and cochlear hearing loss.

4.1.1 *Fusion threshold*

The mean Δf values for fusion thresholds across ISI for normal hearing and individuals with hearing loss is shown in Figure 4.1. Repeated measure ANOVA compared the fusion thresholds across ISIs. The results indicated that there was an overall significant effect of varying ISIs on the fusion thresholds for normal hearing individuals [F (9,61.11) = 2.411, p = 0.015, ŋP^2 = 0.147] and individuals with hearing loss [F (9,262.57) = 3.31, p = 0.001, ŋP^2 = 0.191]. Table 4.1 shows the multiple pairwise comparison results using Bonferroni's correction. The mean fusion thresholds for normal hearing individuals did not vary across the ISI, whereas the variation was observed more for individuals with hearing loss. The mean fusion thresholds obtained for the latter group were lower/better for mid-level ISIs categories (40, 50, 60, 70 ms) compared to lower (10, 20, 30 ms) and higher ISIs (80, 90, 100 ms).

Table 4.1

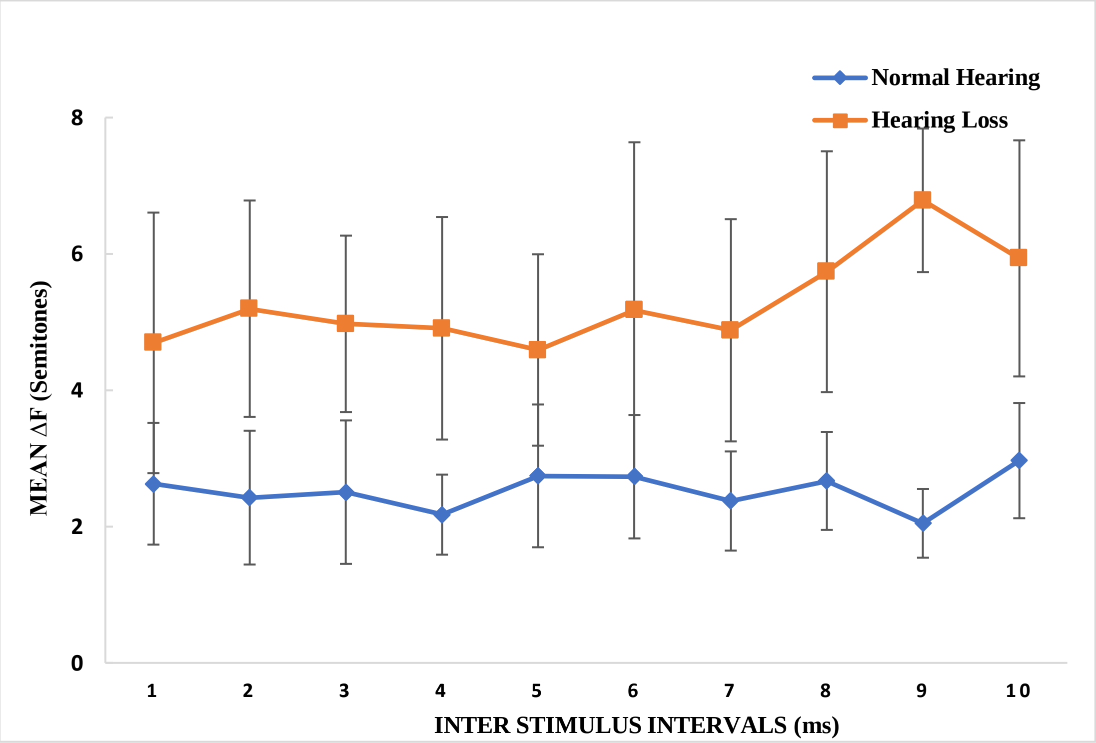
The statistical values showing within-ISI comparison of fusion threshold for individuals with normal hearing and hearing loss.

Comparison between ISIs (ms)	**Normal Hearing**			**Hearing Loss**		
	Mean difference	***SE***	***p-value***	***Mean difference***	***SE***	***p-value***
10 vs 20	0.20	0.31	0.52	-0.50	0.36	0.18
10 vs 30	0.12	0.32	0.71	-0.28	0.57	0.63
10 vs 40	0.45	0.26	0.10	-0.21	0.45	0.64
10 vs 50	-0.12	0.21	0.58	0.10	0.45	0.82
10 vs 60	-0.10	0.28	0.72	-0.48	0.66	0.48
10 vs 70	0.25	0.29	0.39	-0.19	0.35	0.61
10 vs 80	-0.04	0.22	0.85	-1.04	0.45	**0.04***
10 vs 90	0.58	0.25	**0.04***	-2.09	0.61	**0.004***
10 vs 100	-0.34	0.29	0.25	-1.24	0.55	**0.04***
20 vs 30	-0.08	0.18	0.66	0.22	0.45	0.63
20 vs 40	0.25	0.29	0.40	0.29	0.34	0.41
20 vs 50	-0.32	0.34	0.37	0.61	0.49	0.24
20 vs 60	-0.31	0.23	0.19	0.02	0.72	0.98
20 vs 70	0.05	0.25	0.85	0.32	0.40	0.44
20 vs 80	-0.25	0.22	0.28	-0.54	0.48	0.28
20 vs 90	0.38	0.28	0.19	-1.59	0.57	**0.02***
20 vs 100	-0.54	0.27	0.06	-0.74	0.57	0.22
30 vs 40	0.33	0.30	0.28	0.07	0.53	0.90
30 vs 50	-0.24	0.39	0.55	0.38	0.54	0.49
30 vs 60	-0.23	0.31	0.48	-0.20	0.55	0.72
30 vs 70	0.13	0.24	0.60	0.09	0.52	0.86
30 vs 80	-0.16	0.23	0.48	-0.77	0.54	0.18
30 vs 90	0.46	0.27	0.11	-1.81	0.39	**<0.001***
30 vs 100	-0.46	0.30	0.14	-0.96	0.52	0.09
40 vs 50	-0.57	0.27	0.06	0.32	0.43	0.47
40 vs 60	-0.56	0.24	**0.03***	-0.27	0.80	0.74
40 vs 70	-0.20	0.17	0.26	0.03	0.47	0.95
40 vs 80	-0.50	0.18	**0.02***	-0.83	0.55	0.15
40 vs 90	0.13	0.14	0.38	-1.88	0.63	**0.01***
40 vs 100	-0.79	0.13	**<0.001***	-1.03	0.52	0.07
50 vs 60	0.01	0.30	0.97	-0.59	0.68	0.40
50 vs 70	0.37	0.31	0.26	-0.29	0.33	0.40
50 vs 80	0.07	0.22	0.74	-1.15	0.36	**0.01***
50 vs 90	0.70	0.27	**0.02***	-2.20	0.48	**0.00***
50 vs 100	-0.22	0.27	0.41	-1.34	0.38	**0.004***
60 vs 70	0.36	0.30	0.25	0.30	0.59	0.62
60 vs 80	0.06	0.23	0.79	-0.56	0.64	0.39
60 vs 90	0.68	0.28	**0.03***	-1.61	0.58	**0.02***
60 vs 100	-0.24	0.27	0.40	-0.76	0.75	0.32
70 vs 80	-0.29	0.23	0.21	-0.86	0.38	**0.04***
70 vs 90	0.33	0.18	0.09	-1.91	0.55	**0.004***
70 vs 100	-0.59	0.18	**0.01***	-1.06	0.47	**0.04***
80 vs 90	0.62	0.18	**0.004***	-1.05	0.53	0.07
80 vs 100	-0.30	0.18	0.11	-0.20	0.49	0.69
90 vs 100	-0.92	0.20	**<0.001***	0.85	0.55	0.14

Note. *Values in bold are showing significant difference at 95% confidence interval.

Figure 4.1

The mean Δf values for fusion thresholds across ISIs for normal hearing and individuals with hearing loss. Error bars show the standard deviation.



4.1.2 Fission threshold

Figure 4.2 shows the mean Δf values for fission thresholds across ISIs in normal hearing and individuals with hearing loss. Fission thresholds were analysed using Friedmans test to compare the effect of varying ISIs. Results revealed that there was a significant effect of ISI on fission thresholds for normal hearing [$\chi2$ (9) = 23.430, p = 0.005], and hearing loss [$\chi2$ (9) = 28.692, p = 0.001]. Table 4.2 shows the multiple pairwise comparison using Bonferroni's correction.

Table 4.2

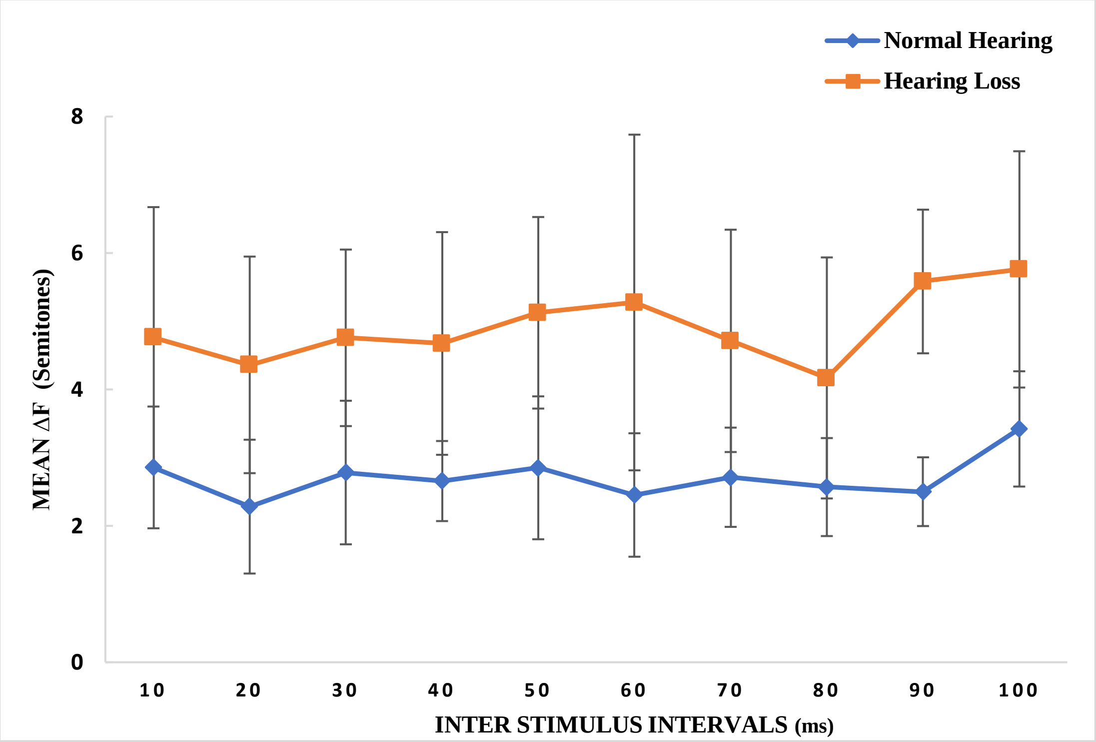
The statistical values showing within-ISI comparison for fission threshold for individuals with normal hearing and hearing loss.

	Normal Hearing				Hearing Loss			
Comparison between ISIs (ms)	***Test statistics***	***SE***	***Standard test statistics***	***p-value***	***Test statistics***	***SE***	***Standard test statistics***	***p-value***
10 vs 20	2.00	1.11	1.81	0.70	1.07	1.11	0.97	0.34
10 vs 30	0.27	1.11	0.24	0.81	0.47	1.11	0.42	0.67
10 vs 40	0.87	1.11	0.78	0.43	0.57	1.11	0.51	0.61
10 vs 50	-0.27	1.11	-0.24	0.81	-0.90	1.11	-0.81	0.42
10 vs 60	1.17	1.11	1.05	0.29	-1.23	1.11	-1.12	0.27
10 vs 70	0.23	1.11	0.21	0.83	0.23	1.11	0.21	0.83
10 vs 80	0.83	1.11	0.75	0.45	1.73	1.11	1.57	0.12
10 vs 90	1.13	1.11	1.03	0.31	-1.67	1.11	-1.51	0.13
10 vs 100	-1.90	1.11	-1.72	0.09	-1.93	1.11	-1.75	0.08
20 vs 30	-1.73	1.11	-1.57	0.12	-0.60	1.11	-0.54	0.59
20 vs 40	-1.13	1.11	-1.03	0.31	-0.50	1.11	-0.45	0.66
20 vs 50	-2.27	1.11	-2.05	**0.04***	-1.97	1.11	-1.78	0.08
20 vs 60	-0.83	1.11	-0.75	0.45	-2.30	1.11	-2.08	**0.04***
20 vs 70	-1.77	1.11	-1.60	0.11	-0.83	1.11	-0.75	0.45
20 vs 80	-1.17	1.11	-1.01	0.29	0.67	1.11	0.60	0.55
20 vs 90	-0.87	1.11	-0.78	0.43	-2.73	1.11	-2.47	**0.01***
20 vs 100	-3.90	1.11	-3.53	<**0.001***	-3.00	1.11	-2.71	**0.01***
30 vs 40	0.60	1.11	0.54	0.59	0.10	1.11	0.09	0.93
30 vs 50	-0.53	1.11	-0.48	0.63	-1.37	1.11	-1.24	0.22
30 vs 60	0.90	1.11	0.81	0.41	-1.70	1.11	-1.54	0.12
30 vs 70	-0.03	1.11	-0.03	0.98	-0.23	1.11	-0.21	0.83
30 vs 80	0.57	1.11	0.51	0.61	1.27	1.11	1.15	0.25
30 vs 90	0.87	1.11	0.78	0.43	-2.13	1.11	-1.93	**0.05***
30 vs 100	-2.17	1.11	-1.9	**0.05***	-2.40	1.11	-2.17	**0.03***
40 vs 50	-1.13	1.11	-1.03	0.31	-1.47	1.11	-1.33	0.19
40 vs 60	0.30	1.11	0.27	0.78	-1.80	1.11	-1.63	0.10
40 vs 70	-0.63	1.11	-0.57	0.57	-0.33	1.11	-0.30	0.76
40 vs 80	-0.03	1.11	-0.03	0.98	1.17	1.11	1.06	0.29
40 vs 90	0.27	1.11	0.24	0.81	-2.23	1.11	-2.02	**0.04***
40 vs 100	-2.77	1.11	-2.50	**0.01***	-2.50	1.11	-2.26	**0.02***
50 vs 60	1.43	1.11	1.30	0.20	-0.33	1.11	-0.30	0.76
50 vs 70	0.50	1.11	0.45	0.65	1.13	1.11	1.03	0.31
50 vs 80	1.10	1.11	0.10	0.32	2.63	1.11	2.38	**0.02***
50 vs 90	1.40	1.11	1.27	0.21	-0.77	1.11	-0.69	0.49
50 vs 100	-1.63	1.11	-1.48	0.14	-1.03	1.11	-0.94	0.35
60 vs 70	-0.93	1.11	-0.84	0.40	1.47	1.11	1.33	0.19
60 vs 80	-0.33	1.11	-0.30	0.76	2.97	1.11	2.69	**0.01***
60 vs 90	-0.03	1.11	-0.03	0.98	-0.43	1.11	-0.39	0.70
60 vs 100	-3.06	1.11	-2.77	**0.01***	-0.70	1.11	-0.63	0.53
70 vs 80	0.60	1.11	0.54	0.59	1.50	1.11	1.36	0.18
70 vs 90	0.90	1.11	0.81	0.42	-1.90	1.11	-1.72	0.09
70 vs 100	-2.13	1.11	-1.93	0.05	-2.17	1.11	-1.96	**0.05***
80 vs 90	0.30	1.11	0.27	0.78	-3.40	1.11	-3.08	**0.002***
80 vs 100	-2.73	1.11	-2.47	**0.01***	-3.67	1.11	-3.32	**0.001***
90 vs 100	-3.03	1.11	-2.74	**0.01***	-0.27	1.11	-0.24	0.81

Note. *Bold values shown significance at 95% confidence interval. SE = Standard error

Figure 4.2

The mean ∆f values for fission thresholds across ISIs for normal hearing and individuals with hearing loss. Error bars shows the standard deviation.



Note. Error bars represent the standard deviation.

These results show that there was a significant effect of ISI on the fusion and fission threshold for individuals with normal hearing and hearing loss. Hence the hypothesis stating that there will be no effect of different ISIs on fusion and fission thresholds in individuals with normal hearing and cochlear hearing loss was rejected.

4.2 The fusion and fission thresholds at different ISIs between individuals with normal hearing and cochlear hearing loss.

4.2.1 Fusion threshold

Figure 4.3 shows the mean fusion thresholds at each ISI for individuals with normal hearing and hearing loss. Repeated measure ANOVA compared the fusion thresholds across ISIs between groups. The results indicated that there was a significant effect of hearing loss on fusion thresholds [F (1,28) = 91.915, $p < 0.001$, $ŋP^2 = 0.767$]. The mean thresholds obtained for normal hearing was significantly lower compared to that of hearing loss. Lower threshold indicates better performance. Table 4.3 shows Pairwise comparison values obtained for fusion thresholds.

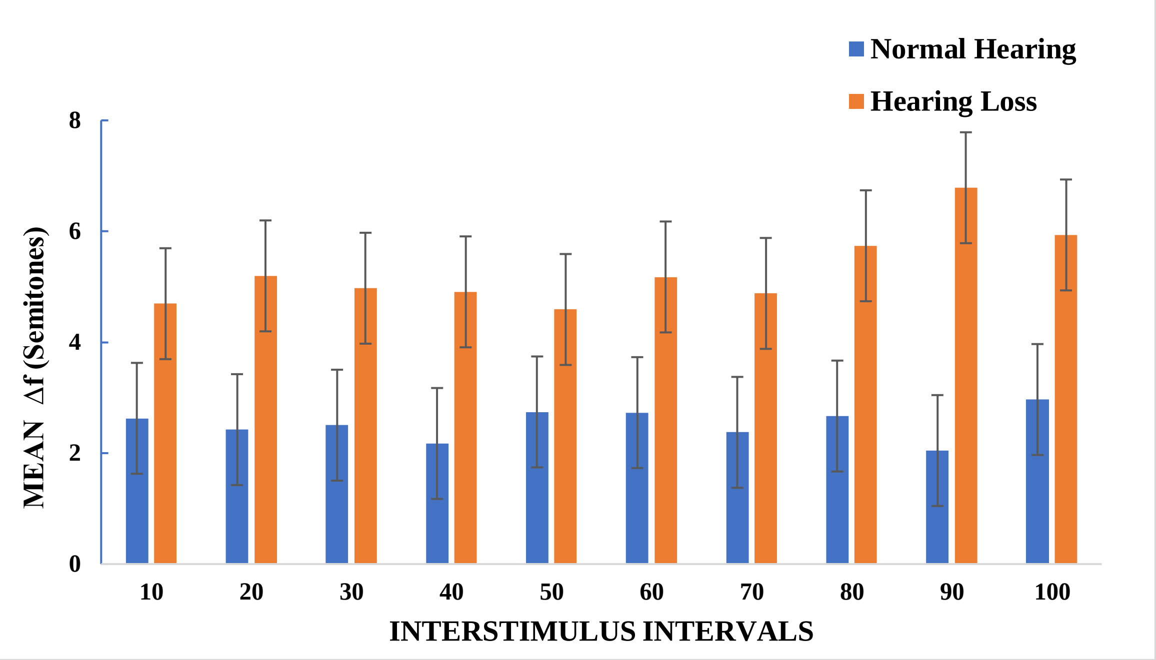
Table 4.3

Pairwise comparison values obtained for fusion thresholds between normal hearing individuals and individuals with hearing loss.

Pairwise comparison of ISI (ms)	t	df	*p* - value
10	-3.497	14	0.004
20	-6.678	14	<0.001
30	-8.596	14	<0.001
40	-6.062	14	<0.001
50	-4.344	14	0.001
60	-3.918	14	0.002
70	-5.921	14	<0.001
80	-6.697	14	<0.001
90	-14.50	14	<0.001
100	-6.493	14	<0.001

Figure 4.3

Mean Δf values for fusion thresholds between individuals with normal hearing and hearing loss. The error-bars shows the standard deviation.



4.2.2 Fission threshold

Mann-Whitney U test compared the fission thresholds across ISIs between individuals with normal hearing and hearing loss. Figure 4.4 shows the mean fission thresholds for individuals with normal hearing and hearing loss across ISIs. The mean thresholds for individuals with normal hearing was significantly lower compared to that of hearing loss. The statistical results are shown in Table 4.4. As noted from the table, there was a significant difference for fission thresholds across all the interstimulus intervals.

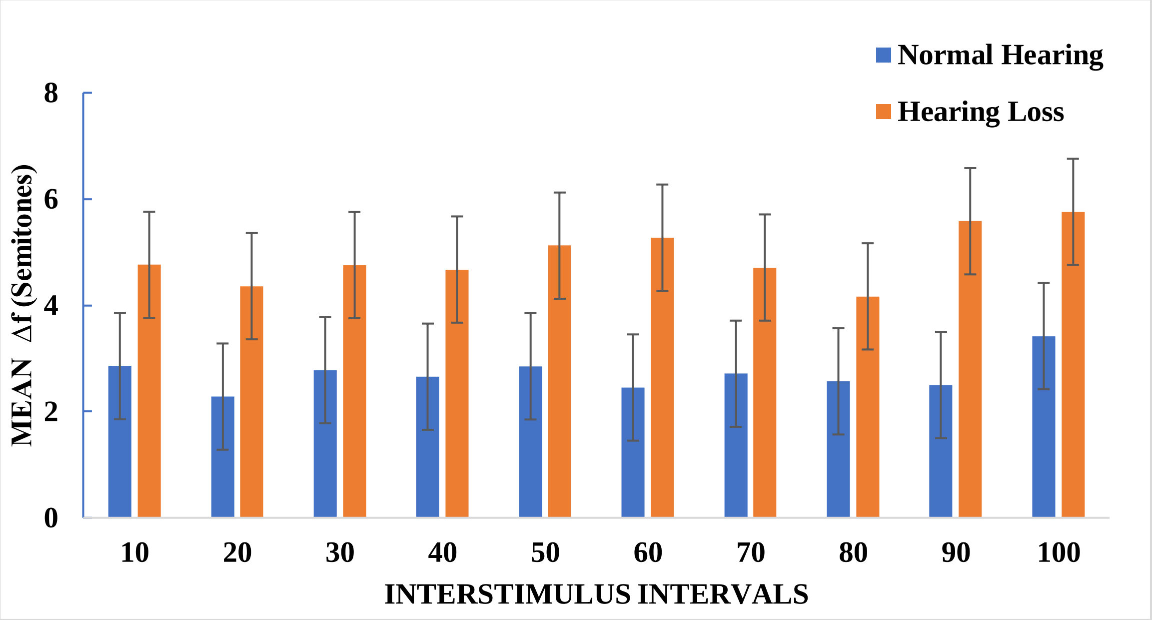
Table 4.4

Mann – Whitney U statistics for comparison between normal hearing and individuals with hearing loss.

ISIs	**Wilcoxon W**	**M-W U**	**Z- values**	**p – values (2 – tailed)**
10	140.00	20.00	-4.03	<0.001
20	132.50	12.50	-4.29	<0.001
30	137.50	17.50	-4.09	<0.001
40	141.00	21.00	-3.98	<0.001
50	142.00	22.00	-3.95	<0.001
60	127.50	7.50	-4.43	<0.001
70	138.00	18.00	-4.05	<0.001
80	155.00	35.00	-3.30	<0.001
90	127.00	7.00	-4.45	<0.001
100	150.00	30.00	-3.49	<0.001

Figure 4.4

Mean Δf values for fission thresholds between individuals with normal hearing and hearing loss. The error-bars shows the standard deviation.



These results show that there was a significant effect of hearing loss on the fusion and fission threshold across ISIs. Hence the hypothesis stating that there will be no difference in the fusion and fission threshold at different ISIs between individuals with normal hearing and hearing loss was rejected.

CHAPTER 5

DISCUSSION

The effect of interstimulus interval on fusion and fission thresholds obtained during stream segregation was measured in the present study. The findings help understand the impact of hearing loss on stream segregation across varying ISIs. The results showed a significant effect of ISI and hearing loss on fusion and fission thresholds.

Auditory stream segregation is fundamental to auditory perception, allowing one to distinguish between sound sources in complex acoustic environments (Bregman et al., 1990). It helps understand how humans perceive and attend to sounds in natural environments, such as conversations in noisy situations or musical performances with multiple instruments (Oxenham, 2018). Auditory stream segregation has implications for the processing designs of hearing aids and cochlear implants (Matz et al., 2022; Paisa et al., 2022; Paredes-Gallardo et al., 2018). It can also help in auditory interventions for individuals with hearing loss (Johnson et al., 2021; Stropahl et al., 2020; Torppa & Huotilainen, 2019).

The stream segregation was measured using the ABA paradigm. It is a widely used experimental paradigm in stream segregation research (Byrne et al., 2019; Deike et al., 2012; Dolležal et al., 2012; Oberfeld, 2014; Simon & Winkler, 2018). It focuses on the auditory system's ability to perceptually organize complex auditory scenes into different auditory streams (Moore et al., 2014). The procedure is straightforward to implement and easier to manipulate and control experimental conditions. It reliably elicits perceptual segregation of the A and B signals into separate streams, even when the physical acoustic properties of A and B are very similar. Such robust effect helps understand the mechanisms of auditory scene analysis.

The present study used a fundamental frequency discrimination task in the ABA paradigm. This task closely mimics real-world auditory perception. Singh in (1987), first used such a task for assessing auditory stream segregation. He found that fundamental frequency can independently contribute to auditory stream segregation. Vliegen and Oxenham (1999b) used a sequence of complex tones with varying F_0 and assessed stream segregation. Grimault et al. (2000) and Bergman et al. (1990) also used an F_0-based paradigm to measure auditory stream segregation. They stated that it is an effective tool for studying auditory stream segregation. It helps understand how the auditory system segregates and groups sounds based on their fundamental frequency differences, which is crucial for auditory scene analysis. The task also provides insights into pitch perception mechanisms. It allows researchers to explore how listeners perceive and discriminate changes in pitch, which is fundamental in understanding how we process and differentiate musical melodies, speech intonation, and other auditory stimuli. Different sound sources emit tones with varying fundamental frequencies in many natural auditory environments. Using the ABA paradigm with a fundamental frequency discrimination task, researchers can closely mimic individuals' challenges when distinguishing between sounds in real-world scenarios, such as music, speech, or environmental sounds.

Bregman et al. (2000) stated that the inter-stimulus interval in the ABA task with fundamental frequency separation could affect the ability of individuals to perceive fusion or fission. This temporal distance, or the distance in time between subsequent sounds, is a salient feature. It was found that as the ISI was reduced, stream segregation improved. ISI within acts as an essential time interval.

Noda et al. (2013a) explored the neural mechanisms underlying auditory stream segregation in rat models by manipulating the intervals between auditory tones, i.e., ISIs. They specifically investigated the potential role of oscillatory phase modulation as a neural correlate of auditory stream segregation. Their findings indicated that higher-frequency bands in the neural responses exhibited a stronger correlation with perceptual boundaries compared to the amplitude of the local field potentials. Furthermore, they observed a gradual increase in responses within approximately three seconds from the onset of the auditory sequence. These results underscored the significance of temporal modulation in cortical oscillations, particularly phase locking, in the perception of auditory streams. This additional insight complements existing theories, such as forward suppression and tonotopic separation, in our understanding of how auditory stream perception is processed in the brain.

Fishman et al. (2004) examined how the ISI affects auditory stream segregation within the auditory cortex of monkeys. They employed an ABAB paradigm, systematically altering the time intervals between tones presented to alert monkeys, all while recording neural activity in the primary auditory cortex. The results of their investigation proposed a physiological model for the process of stream segregation. According to this model, as the ISI increases, it leads to a more pronounced spatial separation of tone responses across the tonotopic map in the primary auditory cortex.

The ISI profoundly impacts auditory signal processing, and manipulation of the same can result in various aspects of perception. Varying ISI can help in auditory discrimination, integration, temporal resolution, and auditory stream segregation and is a commonly used procedure. Efforts have been made to vary the gap duration of such ISIs to identify its effects on stream segregation on normal hearing and cochlear hearing loss.

The present study found that at all levels of ISI, when the frequency separation was less, it always facilitated fusion, and as the difference increased, streaming occurred. These results are consistent with the earlier studies (Bregman et al., 1990). The mean fusion values were less varied in normal hearing individuals, but the variation was observed for individuals with hearing loss. The general trend for normal-hearing individuals was that up to the mid-ISI, some uniformity was maintained. However, at above 80 ms ISI, the variation was higher, and the thresholds were also higher. The higher thresholds could be because tones that are closer in frequency and occur at short ISIs could form links that get stronger. However, tones that are far apart (>80 ms) may take a longer time to get stronger and can get stronger with an increase in repetition of the sequence, perhaps a reason for increased fusion thresholds at higher ISI (Bregman, 1978). Bregman et al. (2000) pointed out that auditory sensory memory might also influence segregation. As the ISI increases, the sensory memory fades, probably leading to increased ambiguity. It may explain why the thresholds could have been poorer.

It was also observed that the fusion threshold was lower at a comparatively low ISI, which could be attributed to its apparent continuity. Sounds that occur more continuously, as provided by a reduction in ISI, tend to be heard more as coherent. It was experimented earlier, where noise bursts were analogous to the ISI (Dannenbring & Bregman, 1976; Warren, 1982). It promotes the integration of the adjacent sounds rather than linking consecutive tones of similar features. It can lead to more integrated percept even when the adjacent sounds markedly differ (Simon & Winkler, 2018). Some findings have been reported for the effect of ISI on the thresholds above 60 ms, but fewer findings are present for ISI less than 60 ms. One such finding is by Simon and Winkler (2018), who have reported that the fusion of sounds is likely to occur more than segregation. Our findings correlate with Simon and Winkler (2018), who have also shown that temporal integration depends on spectral separation and ISI at lower ISIs.

Neurophysiological evidence reports that stream segregation can start at the periphery but extend up to the central systems as the task complexity increases (Snyder & Alain, 2007). While the spectral resolution occurs at the periphery, rate and temporal changes can occur beyond the periphery. However, even though frequency resolution is compromised for individuals with hearing loss, the trend obtained should have been similar to that of normal hearing. However, this was different. The fusion thresholds were better for the mid-ISI compared to low and high. The higher ISI difference has been explained in terms of stimulus links. However, at lower ISIs it is still unclear as to how the temporal processing gets affected for the individuals with hearing loss.

In the present study, we have considered fission as the minimum level at which two streams are perceived and fusion as the maximum level till which sound is heard as one. Looking at the data, we see that at certain ISIs, the fusion is maintained for a longer time and vice versa for other ISIs. There is a region where the responses flip from fusion to fission or vice versa. This refers to the region of ambiguity occurring more frequently for the HI population, indicating that they were unsure about their percept.

Van Noorden (1975) concluded that at shorter ISI, with more Δf, fission precepts were formed. This could occur due to forward masking (Bee & Klump, 2005; Noda et al., 2013b). As the ISI increased, the effectiveness of temporal masking reduced. It was demonstrated that forward masking was often more pronounced when the masker and signal were similar in frequency and when the signal occurred at shorter masking-signal delays. It, consequently, can cause streaming. Below 30 ms, perceiving segregation and integration tend to become approximately equally probable, and the uncertainty of responses starts to increase (Simon & Winkler, 2018).

The origin of where streaming occurs still needs to be clarified. Many electrophysiological studies have been carried out to identify biomarkers or neurophysiological correlates based on EEG and MEG. In the case of passive attention, non-primary auditory and association cortices were seen to be more active than the primary auditory cortex in fMRI studies (Cusack, 2005). On the contrary, thalamocortical interactions are involved in the spontaneous switching of perception, emphasizing the role of the primary auditory cortex. Therefore, thalamocortical inputs in the primary auditory cortex also seem to influence stream segregation (Bidet-Caulet et al., 2007; Kondo & Kashino, 2009; Schadwinkel & Gutschalk, 2010; Wilson et al., 2007). Since our task used active attention, the importance of thalamocortical inputs in stream segregation cannot be neglected. Noda et al. (2013a), in their study of phase locking in stream segregation done in rats, argued that the short ISI leading to fission could indicate that information at hand was transferred to the primary cortex and was represented quite well in cortical oscillation. Beauvois and Meddis (1996) modelled that for a sound to be heard as different, despite falling into different critical bands in the basilar membrane, the sounds should also excite separate neural populations to be heard as segregated. Since individuals with hearing loss have mapping distortions, this could also cause the sounds to be distorted and fall into the same neural population, affecting the perception of segregation.

The effect of varying interstimulus on stream segregation for individuals with hearing loss has not been studied exclusively. Fast presentation rates increases the randomness of the responses due to the increasing uncertainty of these listeners, thereby categorizing their perception according to the available alternatives, causing poorer thresholds at low ISIs (Simon & Winkler, 2018). Higher values of Δf for fusion and fission by individuals indicate their compromised frequency processing. The significant effect of ISI on fusion and fission boundaries showed that temporal processing is also affected in individuals with cochlear hearing loss.

The frequency processing is affected due to cochlear damage, the finding well documented in the literature. (Halliday et al., 2019; Hopkins et al., 2008; Hopkins & Moore, 2007; Moore, 1985; Strelcyk & Dau, 2009). Glasberg and Moore (1990) and Moore and Peters (1992) attributed such variations to altered pitch perception, as seen in individuals with hearing loss. Pitch perception plays a vital role in stream segregation (Oxenham, 2008). Summers and Leek (1998) tested the role of pitch perception in auditory stream segregation in individuals with hearing loss. They found reduced frequency discrimination affecting their stream segregation abilities. The results of the present study showed that hearing loss affects temporal processing. Earlier researchers have attributed cochlear damage to the loss of synapses and reduced phase locking of the auditory nerve, leading to temporal processing deficits (Henry et al., 2016; Moore, 1985; Peterson & Heil, 2019) and supported the present study's findings. However, Harrison and Evans (1979), Miller et al. (1997), and Woolf et al.(1981), found no effect of cochlear pathology on auditory temporal processing. The discrepancy in the results may be attributed to the subjects on which the testing has been carried out. Harrison and Evans (1979) carried out their study on pigs, Miller et al. (1997) on cats, and Woolf et al. (1981) in chinchillas. The auditory signal processing in these animals may differ from that of humans, attributing to the difference in the results.

Rousseau et al. (1983) reported that short-interval thresholds are more impaired in inter-modal timing tasks, which shows that information processing in milliseconds relies more on local channel-specific networks, while longer intervals may be more centralized. However, the categorization of time duration of long or short ISI varies. Most authors have used ISIs more significant than 100 ms, which they consider short. However, in our study, we have taken the ISI range from 10 – 100 ms, which may not be well correlated with the other finding of other research studies.

As the task was done ten times for ten different ISI, the subjects may have also lost attention and been fatigued, which may have played a role in poorer thresholds. Since the listeners with hearing loss have been trying to make up for their hearing by providing more attention to the stimulus at hand, their ability to segregate may have also become better by adapting to their constraints; hence, at few ISIs, their fission thresholds may have been better than fusion thresholds. More insights can be provided based on the effect of ISI on individuals with hearing loss. Of the two factors, in our study, both the spectral cues and the temporal cues play a role in stream segregation, and both of these factors are markedly affected in individuals with hearing loss. Since only mild–moderate hearing loss participants were chosen, there may have been some redundancy that could have played a role. The study indicates that temporal processing is also crucial in stream segregation, but the extent of its involvement is yet to be found.

CHAPTER 6

SUMMARY AND CONCLUSION

The present study aimed to determine the effect of ISI on auditory stream segregation in individuals with normal hearing and cochlear hearing loss. Thirty individuals participated in the study. Group 1 had normal hearing listeners, and group 2 had individuals with hearing loss. After all the routine evaluations, the stream segregation test was done while varying across 10 ISIs. The fusion and fission boundaries were calculated for each individual.

The results revealed a significant effect of varying ISI on the fusion and fission thresholds obtained in each group (Table 5.1). There was also a significant effect of hearing loss on varying ISI. The normal hearing listeners had significantly better fusion and fission thresholds than individuals with hearing loss, as shown in Table 5.2.

While it is known that stream segregation is affected in individuals with cochlear hearing loss due to reduced spectral resolution, the effects of hearing loss on varying temporal factors were still not apparent. This study proved that there is also an effect of temporal variation, so the processing of information temporally is affected in listeners with hearing loss. However, the extent to which it is affected remains unclear. Although ISIs play a role in determining the temporal effects of hearing loss, spectral variation is still considered the paramount factor affecting listeners with hearing loss. The temporal factors can further play a role in rehabilitation strategies for hearing aids or cochlear implants. Further research about the variation of ISIs is needed to know the extent of involvement of processes affected in cochlear hearing loss.

Table 5.1

Effect of varying interstimulus intervals on normal hearing and individuals with hearing loss

	Normal	**Hearing loss**
Fusion	Significant	Significant
Fission	Significant	Significant

Table 5.2

Effect of hearing loss on fusion and fission thresholds

	Fusion	Fission
Normal vs HL	Significant	Significant

Implications of the study

The outcome of this study may help in understanding the impact of cochlear damage on auditory temporal processing abilities. Whether stream segregation is a complete peripheral process or includes neural mechanisms is still a dilemma. This study contributes to understanding the processing better. As cochlea functions for both frequency and temporal processing, this study may help understand the impact of cochlear damage on signal perception. ISI can also have a role in rehabilitating hearing loss whereby changing the stimulus intervals can lead to fusion or fission percept, acting as a cue for frequency selectivity and discrimination of speech sounds. The ever-growing technology can implement strategies based on ISI whereby it can adaptively change the stimulus interval to assist the patient in integrating/ separating/ sounds, thereby making the patient an effective communicator, which can be piloted in hearing aids and cochlear implants.

In summary, many studies have been conducted that have conflicting conclusions; some studies have shown that temporal processing can be affected by cochlear hearing loss, while other authors have shown otherwise. Many factors could have played a role in such variable findings, like the medium of instruction, the task to be done, attention, the type of stimulus used, the paradigm used, etc. The processes occurring in stream segregation are still unknown, and this study can add to the literature and provide required conclusions.

Strengths of the study

- The study is the first of its kind to investigate the effect of ISI on fusion and fission thresholds in individuals with hearing loss.
- The study can help understand the effect of cochlear hearing loss on stream segregation with varying ISIs.
- The study can help understand the effect of cochlear hearing loss on the temporal processing of sounds.
- Since the study used a speech sound, it is more relevant to natural stimuli.

Limitations of the study

- The study was done only on 15 individuals with hearing loss. A larger sample size could have given us better results.
- The stimulus used was a synthetic speech sound. There could have been some distortions that the individuals with cochlear hearing loss may have faced.

- Stimuli could have been taken at the level of words or sentences, which is natural.
- The time taken was long, so the participant's interests may have varied.

Future directions

- Although our study has proved that temporal processing affects individuals with hearing loss, the extent to which it gets affected is still unknown. More research in this field could give us consistent results.
- This study has taken only up to 100 ms, which can be expanded up to 300 ms since some researchers have proved that HI individuals require more ISI to perceive differences, so based on the values obtained, best ISIs and poorer ISIs can be categorized.
- Knowing at what level of ISI, fusion, or fission occurs, many rehabilitation paradigms can be researched to benefit the hearing-impaired population. Piloting of hearing aids can then be compared with normal hearing groups, and the amount of benefit obtained from varying ISIs can be known to a greater significance.
- In our study, fusion and fission thresholds were not compared with each other. Since there is a region of ambiguity, the thresholds for individuals' hearing loss can be compared to see to what extent fusion is perceived from when fission occurs and how it varies with that of normal hearing individuals.

REFERENCES

Anstis, S., & Saida, S. (1985). Adaptation to Auditory Streaming of Frequency-Modulated Tones. *Journal of Experimental Psychology: Human Perception and Performance*, *11*(3), 257–271. https://doi.org/10.1037/0096-1523.11.3.257

Banerjee, N., & Prabhu, P. (2021). Evaluation of auditory stream segregation in individuals with cochlear pathology and auditory neuropathy spectrum disorder. *Auditory and Vestibular Research*, *30*(3), 176–182. https://doi.org/10.18502/AVR.V30I3.6531

Beauvois, M. W. (1998). The effect of tone duration on auditory stream formation. *Perception & Psychophysics, 60*(5), 852–861. https://doi.org/10.3758/BF03206068

Beauvois, M. W., & Meddis, R. (1996). Computer simulation of auditory stream segregation in alternating-tone sequences. *The Journal of the Acoustical Society of America*, *99*(4 Pt 1), 2270–2280. https://doi.org/10.1121/1.415414

Bee, M. A., & Klump, G. M. (2005). Auditory Stream Segregation in the Songbird Forebrain: Effects of Time Intervals on Responses to Interleaved Tone Sequences. *Brain Behavior and Evolution*, *66*(3), 197–214. https://doi.org/10.1159/000087854

Bidet-Caulet, A., Fischer, C., Besle, J., Aguera, P. E., Giard, M. H., & Bertrand, O. (2007). Effects of Selective Attention on the Electrophysiological Representation of Concurrent Sounds in the Human Auditory Cortex. *Journal of Neuroscience, 27*(35), 9252–9261. https://doi.org/10.1523/JNEUROSCI.1402-07.2007

Bregman, A. S. (1978). Auditory streaming is cumulative. *Journal of Experimental Psychology: Human Perception and Performance*, *4*(3), 380–387.

https://doi.org/10.1037/0096-1523.4.3.380

Bregman, A. S. (1990). *Auditory Scene Analysis: The Perceptual Organization of Sound*. https://doi.org/10.7551/MITPRESS/1486.001.0001

Bregman, A. S., Ahad, P. A., Crum, P. A. C., & O'Reilly, J. (2000). Effects of time intervals and tone durations on auditory stream segregation. *Perception and Psychophysics*, *62*(3), 626–636. https://doi.org/10.3758/BF03212114

Bregman, A. S., Liao, C., & Levitan, R. (1990). Auditory grouping based on fundamental frequency and formant peak frequency. *Canadian Journal of Psychology*, *44*(3), 400–413. https://doi.org/10.1037/H0084255

Bregman, A. S., & McAdams, S. (1994). Auditory Scene Analysis: The Perceptual Organization of Sound. *The Journal of the Acoustical Society of America*, *95*(2), 1177–1178. https://doi.org/10.1121/1.408434

Bregman, A. S., & McAdams, S. (1998). Auditory Scene Analysis: The Perceptual Organization of Sound. *The Journal of the Acoustical Society of America*, *95*(2), 1177. https://doi.org/10.1121/1.408434

Byrne, Á., Rinzel, J., & Rankin, J. (2019). Auditory streaming and bistability paradigm extended to a dynamic environment. *Hearing Research*, *383*, 107807. https://doi.org/10.1016/J.HEARES.2019.107807

Carlyon, R. P., Plack, C. J., Fantini, D. A., & Cusack, R. (2003). Cross-Modal and Non-Sensory Influences on Auditory Streaming. *Http://Dx.Doi.Org/10.1068/P5035*, *32*(11), 1393–1402. https://doi.org/10.1068/P5035

Cherry, E. C. (1953). Some Experiments on the Recognition of Speech, with One and with Two Ears. *The Journal of the Acoustical Society of America*, *25*(5), 975–979. https://doi.org/10.1121/1.1907229

Cusack, R. (2005). The Intraparietal Sulcus and Perceptual Organization. *Journal of Cognitive Neuroscience*, *17*(4), 641–651. https://doi.org/10.1162/0898929053467541

Cusack, R., & Roberts, B. (1999). Effects of similarity in bandwidth on the auditory sequential streaming of two-tone complexes. *Perception, 28*(10), 1281–1289. https://doi.org/10.1068/P2804

Dannenbring, G. L., & Bregman, A. S. (1976). Stream segregation and the illusion of overlap. *Journal of Experimental Psychology: Human Perception and Performance*, *2*(4), 544–555. https://doi.org/10.1037/0096-1523.2.4.544

Darwin, C. J. (2008). Listening to speech in the presence of other sounds. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1493), 1011–1021. https://doi.org/10.1098/RSTB.2007.2156

David, M., Tausend, A. N., Strelcyk, O., & Oxenham, A. J. (2018). Effect of age and hearing loss on auditory stream segregation of speech sounds. *Hearing Research*, *364,* 118. https://doi.org/10.1016/J.HEARES.2018.03.017

Deike, S., Heil, P., Böckmann-Barthel, M., & Brechmann, A. (2012). The build-up of auditory stream segregation: A different perspective. *Frontiers in Psychology*, *3*(OCT), 33725. https://doi.org/10.3389/FPSYG.2012.00461/BIBTEX

Dolležal, L. V., Beutelmann, R., & Klump, G. M. (2012). Stream segregation in the perception of sinusoidally amplitude-modulated tones. *PloS One, 7*(9). https://doi.org/10.1371/JOURNAL.PONE.0043615

Feldman, A. S. (1976). Tympanometry: application and interpretation. *Annals of Otology, Rhinology and Laryngology*, *85*(Sup.25), 202–208. https://doi.org/10.1177/00034894760850S238

Fishman, Y. I., Arezzo, J. C., & Steinschneider, M. (2004). Auditory stream segregation in monkey auditory cortex: effects of frequency separation, presentation rate, and tone duration. *The Journal of the Acoustical Society of America*, *116*(3), 1656–1670. https://doi.org/10.1121/1.1778903

Fletcher, H. (1940). Auditory Patterns. *Reviews of Modern Physics*, *12*(1), 47. https://doi.org/10.1103/RevModPhys.12.47

Fuglsang, S. A., Märcher-Rørsted, J., Dau, T., & Hjortkjær, J. (2020). Effects of Sensorineural Hearing Loss on Cortical Synchronization to Competing Speech during Selective Attention. *The Journal of Neuroscience*, *40*(12), 2562. https://doi.org/10.1523/JNEUROSCI.1936-19.2020

Glasberg, B. R., & Moore, B. C. J. (1986). Auditory filter shapes in subjects with unilateral and bilateral cochlear impairments. *The Journal of the Acoustical Society of America*, *79*(4), 1020–1033. https://doi.org/10.1121/1.393374

Glasberg, B. R., & Moore, B. C. J. (1990). Derivation of auditory filter shapes from notched-noise data. *Hearing Research*, *47*(1–2), 103–138. https://doi.org/10.1016/0378-5955(90)90170-T

Gockel, H., Carlyon, R. P., & Micheyl, C. (1999). Context dependence of fundamental-frequency discrimination: Lateralized temporal fringes. *The Journal of the Acoustical Society of America*, *106*(6), 3553. https://doi.org/10.1121/1.428208

Grimault, N., Bacon, S. P., & Micheyl, C. (2002). Auditory stream segregation on the basis of amplitude-modulation rate. *The Journal of the Acoustical Society of America*, *111*(3), 1340. https://doi.org/10.1121/1.1452740

Grimault, N., Micheyl, C., Carlyon, R. P., Arthaud, P., & Collet, L. (2000). Influence of peripheral resolvability on the perceptual segregation of harmonic complex tones differing in fundamental frequency. *The Journal of the Acoustical Society of America*, *108*(1), 263–271. https://doi.org/10.1121/1.429462

Grimault, N., Micheyl, C., Carlyon, R. P., Arthaud, P., & Collet, L. (2001). Perceptual auditory stream segregation of sequences of complex sounds in subjects with normal and impaired hearing. *Http://Dx.Doi.Org/10.1080/00305364.2001.11745235*, *35*(3), 173–182. https://doi.org/10.1080/00305364.2001.11745235

Halliday, L. F., Rosen, S., Tuomainen, O., & Calcus, A. (2019). Impaired frequency selectivity and sensitivity to temporal fine structure, but not envelope cues, in children with mild-to-moderate sensorineural hearing loss. *The Journal of the Acoustical Society of America*, *146*(6), 4299–4314. https://doi.org/10.1121/1.5134059

Harrison, R. V., & Evans, E. F. (1979). Some aspects of temporal coding by single cochlear fibres from regions of cochlear hair cell degeneration in the guinea pig. *Archives of Oto-Rhino-Laryngology*, *224*(1–2), 71–78. https://doi.org/10.1007/BF00455226/METRICS

Hartmann, W. M., & Johnson, D. (1991). Stream Segregation and Peripheral Channeling. *Music Perception*, *9*(2), 155–183. https://doi.org/10.2307/40285527

Haywood, N. R., & Roberts, B. (2011). Effects of inducer continuity on auditory stream segregation: comparison of physical and perceived continuity in different contexts. *The Journal of the Acoustical Society of America*, *130*(5), 2917–2927. https://doi.org/10.1121/1.3643811

Henry, K. S., Kale, S., & Heinz, M. G. (2016). Distorted Tonotopic Coding of Temporal Envelope and Fine Structure with Noise-Induced Hearing Loss. *The Journal of Neuroscience*, *36*(7), 2227. https://doi.org/10.1523/JNEUROSCI.3944-15.2016

Hopkins, K., & Moore, B. C. J. (2007). Moderate cochlear hearing loss leads to a reduced ability to use temporal fine structure information. *The Journal of the Acoustical Society of America*, *122*(2), 1055–1068. https://doi.org/10.1121/1.2749457

Hopkins, K., Moore, B. C. J., & Stone, M. A. (2008). Effects of moderate cochlear hearing loss on the ability to benefit from temporal fine structure information in speech. *The Journal of the Acoustical Society of America*, *123*(2), 1140. https://doi.org/10.1121/1.2824018

Houtsma, A. J. M., & Smurzynski, J. (1998). Pitch identification and discrimination for complex tones with many harmonics. *The Journal of the Acoustical Society of America*, *87*(1), 304. https://doi.org/10.1121/1.399297

Iverson, P. (1995). Auditory Stream Segregation by Musical Timbre: Effects of Static and Dynamic Acoustic Attributes. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(4), 751–763. https://doi.org/10.1037/0096-1523.21.4.751

Jerger, J. (1970). Clinical Experience With Impedance Audiometry. *Archives of Otolaryngology*, *92*(4), 311–324.

https://doi.org/10.1001/ARCHOTOL.1970.04310040005002

Johnson, N., Shiju, A. M., Parmar, A., & Prabhu, P. (2021). Evaluation of Auditory Stream Segregation in Musicians and Nonmusicians. *International Archives of Otorhinolaryngology*, *25*(1), e77. https://doi.org/10.1055/S-0040-1709116

Jones, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychological Review*, 83(5), 323–355. https://doi.org/10.1037/0033-295x.83.5.323

Klatt, D. H. (1998). Software for a cascade/parallel formant synthesizer. *The Journal of the Acoustical Society of America*, *67*(3), 971. https://doi.org/10.1121/1.383940

Kondo, H. M., & Kashino, M. (2009). Involvement of the Thalamocortical Loop in the Spontaneous Switching of Percepts in Auditory Streaming. *Journal of Neuroscience*, *29*(40), 12695–12701. https://doi.org/10.1523/JNEUROSCI.1549-09.2009

Lidén, G., Harford, E., & Hallén, O. (1974). Automatic tympanometry in clinical practice. *Audiology : Official Organ of the International Society of Audiology*, *13*(2), 126–139. https://doi.org/10.3109/00206097409071671

Matz, A. F., Nie, Y., & Wheeler, H. J. (2022). Auditory stream segregation of amplitude-modulated narrowband noise in cochlear implant users and individuals with normal hearing. *Frontiers in Psychology*, *13*, 927854. https://doi.org/10.3389/FPSYG.2022.927854/BIBTEX

McCabe, S. L., & Denham, M. J. (1997). A model of auditory streaming. *NIPS 1995: Proceedings of the 8th International Conference on Neural Information*

Processing Systems, 52–58. https://doi.org/10.1121/1.418176

Miller, R. L., Schilling, J. R., Franck, K. R., & Young, E. D. (1997). Effects of acoustic trauma on the representation of the vowel “eh” in cat auditory nerve fibers. *The Journal of the Acoustical Society of America*, *101*(6), 3602–3616. https://doi.org/10.1121/1.418321

Moore, B. C. J. (1985). Frequency selectivity and temporal resolution in normal and hearing-impaired listeners. *British Journal of Audiology*, *19*(3), 189–201. https://doi.org/10.3109/03005368509078973

Moore, B. C. J. (1995a). Frequency Analysis and Masking. *Hearing*, 161–205. https://doi.org/10.1016/B978-012505626-7/50007-8

Moore, B. C. J. (1995b). Perceptual Consequences of Cochlear Damage. *Perceptual Consequences of Cochlear Damage*. https://doi.org/10.1093/ACPROF:OSO/9780198523307.001.0001

Moore, B. C. J. (2002). Psychoacoustics of normal and impaired hearing. *British Medical Bulletin*, *63*(1), 121–134. https://doi.org/10.1093/BMB/63.1.121

Moore, B. C. J., Füllgrabe, C., & F€ Ullgrabe, C. (2014). Effects of age and hearing loss on stream segregation based on interaural time differences. *The Journal of the Acoustical Society of America*, *136*(2), EL185–EL191. https://doi.org/10.1121/1.4890201

Moore, B. C. J., & Glasberg, B. R. (1983). Suggested formulae for calculating auditory-filter bandwidths and excitation patterns. *The Journal of the Acoustical Society of America*, *74*(3), 750–753. https://doi.org/10.1121/1.389861

Moore, B. C. J., & Gockel, H. E. (2002). *Factors Influencing Sequential Stream*

Segregation. *88*, 320–332. https://www.researchgate.net/publication/246159634

Moore, B. C. J., & Gockel, H. E. (2012). Properties of auditory stream formation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1591), 919. https://doi.org/10.1098/RSTB.2011.0355

Moore, B. C. J., & Peters, R. W. (1992). Pitch discrimination and phase sensitivity in young and elderly subjects and its relationship to frequency selectivity. *The Journal of the Acoustical Society of America*, *91*(5), 2881–2893. https://doi.org/10.1121/1.402925

Noda, T., Kanzaki, R., & Takahashi, H. (2013a). Stimulus phase locking of cortical oscillation for auditory stream segregation in rats. *PloS One*, *8*(12). https://doi.org/10.1371/JOURNAL.PONE.0083544

Noda, T., Kanzaki, R., & Takahashi, H. (2013b). Stimulus Phase Locking of Cortical Oscillation for Auditory Stream Segregation in Rats. *PLoS ONE*, *8*(12), 83544. https://doi.org/10.1371/JOURNAL.PONE.0083544

Noorden, L. V. (1975). *Temporal coherence in the perception of tone sequences*. PhD Thesis. University of Technology, Eindhoven, The Netherlands

Oberfeld, D. (2014). An objective measure of auditory stream segregation based on molecular psychophysics. *Attention, Perception, and Psychophysics*, *76*(3), 829–851. https://doi.org/10.3758/S13414-013-0613-Z

Oxenham, A. J. (2008). Pitch Perception and Auditory Stream Segregation: Implications for Hearing Loss and Cochlear Implants. *Trends in Amplification*, *12*(4), 316. https://doi.org/10.1177/1084713808325881

P, J. Antony., & Barman, A. (2021). Auditory stream segregation with sinusoidally amplitude modulated tonal stimuli in individuals with sensorineural hearing loss. *Journal of Hearing Science*, *11*(1), 31–39. https://doi.org/10.17430/JHS.2021.11.1.3

Paisa, R., Cavdir, D., Ganis, F., Williams, P., & Serafin, S. (2022). *Multisensory Integration Design in Music for Cochlear Implant Users*. https://doi.org/10.5281/ZENODO.6573315

Paredes-Gallardo, A., Madsen, S. M. K., Dau, T., & Marozeau, J. (2018). The Role of Temporal Cues in Voluntary Stream Segregation for Cochlear Implant Users. *Trends in Hearing*, *22*. https://doi.org/10.1177/2331216518773226/ASSET/IMAGES/LARGE/10.1177_2331216518773226-FIG6.JPEG

Peterson, A. J., & Heil, P. (2019). Phase Locking of Auditory-Nerve Fibers Reveals Stereotyped Distortions and an Exponential Transfer Function with a Level-Dependent Slope. *The Journal of Neuroscience*, *39*(21), 4077. https://doi.org/10.1523/JNEUROSCI.1801-18.2019

Roberts, B., Glasberg, B. R., & Moore, B. C. J. (2002). Primitive stream segregation of tone sequences without differences in fundamental frequency or passband. *The Journal of the Acoustical Society of America*, *112*(5), 2074. https://doi.org/10.1121/1.1508784

Rose, M. M., & Moore, B. C. J. (1997). Perceptual grouping of tone sequences by normally hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America*, *102*(3), 1768–1778. https://doi.org/10.1121/1.420108

Rose, M. M., & Moore, B. C. J. (2005). The relationship between stream segregation and frequency discrimination in normally hearing and hearing-impaired subjects.

Hearing Research, *204*(1–2), 16–28. https://doi.org/10.1016/J.HEARES.2004.12.004

Rousseau, R., Poirier, J., & Lemyre, L. (1983). Duration discrimination of empty time intervals marked by intermodal pulses. *Perception & Psychophysics*, *34*(6), 541–548. https://doi.org/10.3758/BF03205907/METRICS

Schadwinkel, S., & Gutschalk, A. (2010). Activity Associated with Stream Segregation in Human Auditory Cortex is Similar for Spatial and Pitch Cues. *Cerebral Cortex*, *20*(12), 2863–2873. https://doi.org/10.1093/CERCOR/BHQ037

Shearer, D. E., Molis, M. R., Bennett, K. O., & Leek, M. R. (2018). Auditory stream segregation of iterated rippled noises by normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America*, *143*(1), 378. https://doi.org/10.1121/1.5021333

Simon, J., & Winkler, I. (2018). The Role of Temporal Integration in Auditory Stream Segregation. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(11), 1683–1693. https://doi.org/10.1037/XHP0000564

Singh, P. G. (1987). Perceptual organization of complex-tone sequences: A tradeoff between pitch and timbre. *Journal of the Acoustical Society of America*, *82*(3), 886–899. https://doi.org/10.1121/1.395287

Singh, P. G., & Bregman, A. S. (1998). The influence of different timbre attributes on the perceptual segregation of complex-tone sequences. *The Journal of the Acoustical Society of America*, *102*(4), 1943. https://doi.org/10.1121/1.419688

Snyder, J. S., & Alain, C. (2007). Toward a neurophysiological theory of auditory stream segregation. *Psychological Bulletin*, *133*(5), 780–799.

https://doi.org/10.1037/0033-2909.133.5.780

Spielmann, M., Schröger, E., Kotz, S. A., Pechmann, T., & Bendixen, A. (2013). Using a staircase procedure for the objective measurement of auditory stream integration and segregation thresholds. *Frontiers in Psychology*, *4*, 534. https://doi.org/10.3389/fpsyg.2013.00534

Stainsby, T. H., Moore, B. C. J., & Glasberg, B. R. (2004). Auditory streaming based on temporal structure in hearing-impaired listeners. *Hearing Research*, *192*(1–2), 119–130. https://doi.org/10.1016/J.HEARES.2004.02.003

Strelcyk, O., & Dau, T. (2009). Relations between frequency selectivity, temporal fine-structure processing, and speech reception in impaired hearing. *The Journal of the Acoustical Society of America*, *125*(5), 3328. https://doi.org/10.1121/1.3097469

Stropahl, M., Besser, J., & Launer, S. (2020). Auditory Training Supports Auditory Rehabilitation: A State-of-the-Art Review. *Ear and Hearing*, *41*(4), 697–704. https://doi.org/10.1097/AUD.0000000000000806

Summers, V., & Leek, M. R. (1998). FO processing and the separation of competing speech signals by listeners with normal hearing and with hearing loss. *Journal of Speech, Language, and Hearing Research : JSLHR*, *41*(6), 1294–1306. https://doi.org/10.1044/JSLHR.4106.1294

Thomas, I. B., Cetti, R. P., & Chase, P. W. (1971). Effect of Silent Intervals on the Perception of Temporal Order for Vowels. *The Journal of the Acoustical Society of America*, *49*(1A_Supplement), 85–85. https://doi.org/10.1121/1.1976065

Thompson. (2004). Effects of location, frequency region, and time course of selective attention on auditory scene analysis. *Journal of Experimental Psychology. Human Perception and Performance*, *30*(4), 643–656. https://doi.org/10.1037/0096-1523.30.4.643

Torppa, R., & Huotilainen, M. (2019). Why and how music can be used to rehabilitate and develop speech and language skills in hearing-impaired children. *Hearing Research*, *380*, 108–122. https://doi.org/10.1016/J.HEARES.2019.06.003

Valentine, S., & Lentz, J. J. (2008). Broadband auditory stream segregation by hearing-impaired and normal-hearing listeners. *Journal of Speech, Language, and Hearing Research : JSLHR*, *51*(5), 1341–1352. https://doi.org/10.1044/1092-4388(2008/07-0193)

Vliegen, J., Moore, B. C. J., & Oxenham, A. J. (1999a). The role of spectral and periodicity cues in auditory stream segregation, measured using a temporal discrimination task. *The Journal of the Acoustical Society of America*, *106*(2), 938–945. https://doi.org/10.1121/1.427140

Vliegen, J., Moore, B. C. J., & Oxenham, A. J. (1999b). The role of spectral and periodicity cues in auditory stream segregation, measured using a temporal discrimination task. *The Journal of the Acoustical Society of America*, *106*(2), 938–945. https://doi.org/10.1121/1.427140

Vliegen, J., & Oxenham, A. J. (1999). Sequential stream segregation in the absence of spectral cues. *The Journal of the Acoustical Society of America*, *105*(1), 97. https://doi.org/10.1121/1.424503

Warren, R. M. (1982).Auditory perception: A new synthesis. Elmsford, NY: Pergamon.

Warren, R. M., & Warren, R. P. (1970). Auditory illusions and confusions. *Scientific American*, *223*(6), 30–36. https://doi.org/10.1038/SCIENTIFICAMERICAN1270-30

Wilson, E. C., Melcher, J. R., Micheyl, C., Gutschalk, A., & Oxenham, A. J. (2007). Cortical fMRI activation to sequences of tones alternating in frequency: Relationship to perceived rate and streaming. *Journal of Neurophysiology*, *97*(3), 2230–2238. https://doi.org/10.1152/JN.00788.2006/ASSET/IMAGES/LARGE/Z9K0030780460005.JPEG

Woolf, N. K., Ryan, A. F., & Bone, R. C. (1981). Neural phase-locking properties in the absence of cochlear outer hair cells. *Hearing Research*, *4*(3–4), 335–346. https://doi.org/10.1016/0378-5955(81)90017-4

Wright, H. N. (1968). The Effect of Sensori-Neural Hearing Loss on Threshold-Duration Functions. *Journal of Speech and Hearing Research*, *11*(4), 842–852. https://doi.org/10.1044/JSHR.1104.842