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ASSESSMENT OF BINAURAL BENEFITS IN HEARING AND HEARING IMPAIRED LISTENERS

B.S. AUD. Okan ÖZ

Audiology Programme
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ANKARA
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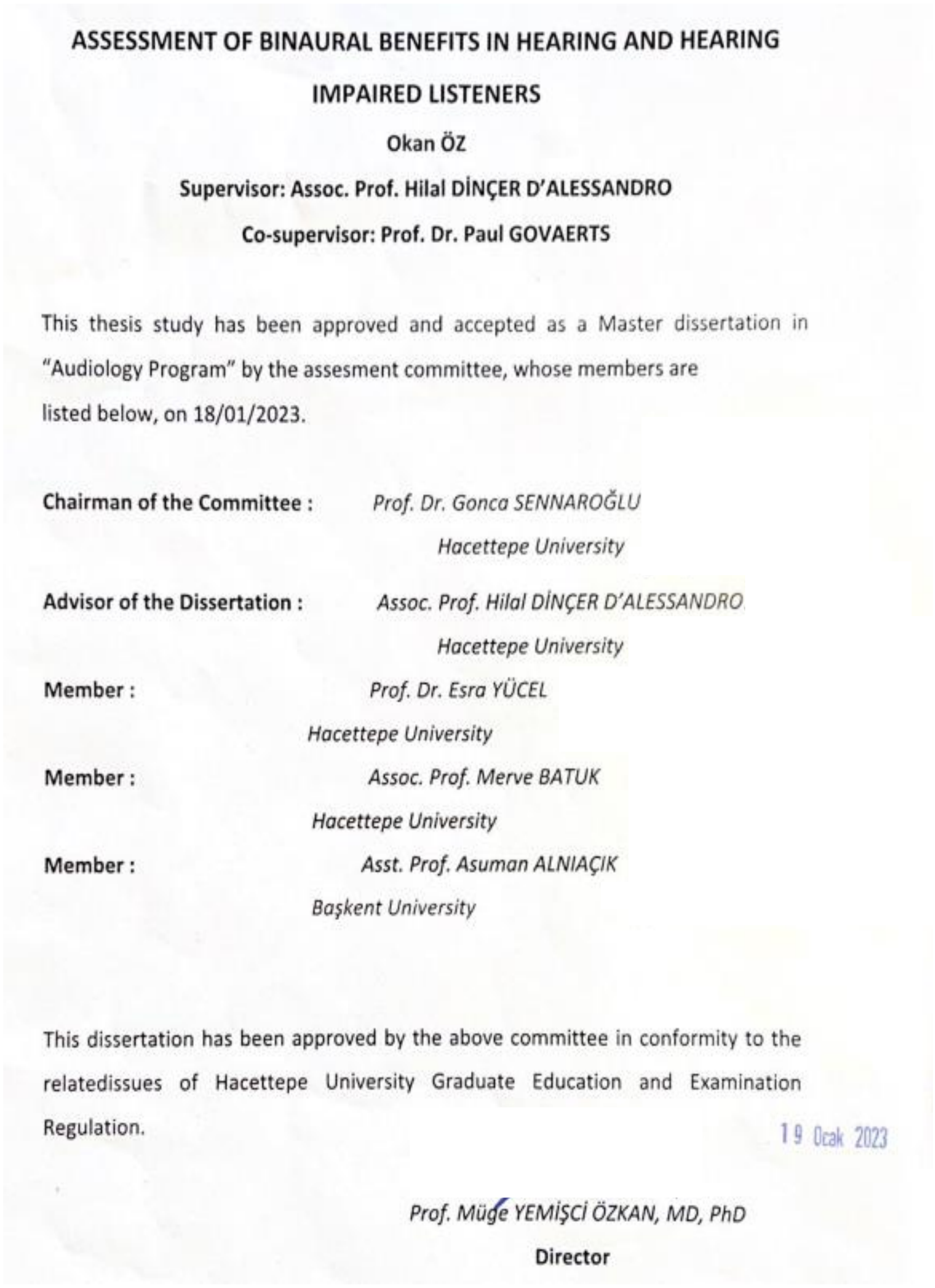

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YAYIMLAMA VE FİKRİ MÜLKİYET HAKLARI BEYANI

Enstitü tarafından onaylanan lisansüstü tezimin/raporumun tamamını veya herhangi bir kısmını, basılı (kağıt) ve elektronik formatta arşivleme ve aşağıda verilen koşullarla kullanıma açma iznini Hacettepe Üniversitesine verdiğimi bildiririm. Bu izinle Üniversiteye verilen kullanım hakları dışındaki tüm fikri mülkiyet haklarım bende kalacak, tezimin tamamının ya da bir bölümünün gelecekteki çalışmalarda (makale, kitap, lisans ve patent vb.) kullanım hakları bana ait olacaktır.

Tezin kendi orijinal çalışmam olduğunu, başkalarının haklarını ihlal etmediğimi ve tezimin tek yetkili sahibi olduğumu beyan ve taahhüt ederim. Tezimde yer alan telif hakkı bulunan ve sahiplerinden yazılı izin alınarak kullanılması zorunlu metinlerin yazılı izin alınarak kullandığımı ve istenildiğinde suretlerini Üniversiteye teslim etmeyi taahhüt ederim.

Yükseköğretim Kurulu tarafından yayınlanan ***"Lisansüstü Tezlerin Elektronik Ortamda Toplanması, Düzenlenmesi ve Erişime Açılmasına İlişkin Yönerge"*** kapsamında tezim aşağıda belirtilen koşullar haricince YÖK Ulusal Tez Merkezi / H.Ü. Kütüphaneleri Açık Erişim Sisteminde erişime açılır.

○ Enstitü / Fakülte yönetim kurulu kararı ile tezimin erişime açılması mezuniyet tarihimden itibaren 2 yıl ertelenmiştir. (1)

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○ Tezimle ilgili gizlilik kararı verilmiştir. (3)

18/01/2023

Okan ÖZ

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[1] *"Lisansüstü Tezlerin Elektronik Ortamda Toplanması, Düzenlenmesi ve Erişime Açılmasına İlişkin Yönerge"*

(1) *Madde 6. 1. Lisansüstü tezle ilgili patent başvurusu yapılması veya patent alma sürecinin devam etmesi durumunda, tez **danışmanının** önerisi ve **enstitü anabilim dalının** uygun görüşü üzerine **enstitü** veya **fakülte yönetim kurulu** iki yıl süre ile tezin erişime açılmasının ertelenmesine karar verebilir.*

(2) *Madde 6. 2. Yeni teknik, materyal ve metotların kullanıldığı, henüz makaleye dönüşmemiş veya patent gibi yöntemlerle korunmamış ve internetten paylaşılması durumunda 3. şahıslara veya kurumlara haksız kazanç imkanı oluşturabilecek bilgi ve bulguları içeren tezler hakkında tez **danışmanının** önerisi ve **enstitü anabilim dalının** uygun görüşü üzerine **enstitü** veya **fakülte yönetim kurulunun** gerekçeli kararı ile altı ayı aşmamak üzere tezin erişime açılması engellenebilir.*

(3) *Madde 7. 1. Ulusal çıkarları veya güvenliği ilgilendiren, emniyet, istihbarat, savunma ve güvenlik, sağlık vb. konulara ilişkin lisansüstü tezlerle ilgili gizlilik kararı, **tezin yapıldığı kurum** tarafından verilir *. Kurum ve kuruluşlarla yapılan işbirliği protokolü çerçevesinde hazırlanan lisansüstü tezlere ilişkin gizlilik kararı ise, **ilgili kurum ve kuruluşun önerisi** ile **enstitü** veya **fakültenin** uygun görüşü üzerine **üniversite yönetim kurulu** tarafından verilir. Gizlilik kararı verilen tezler Yükseköğretim Kuruluna bildirilir.*
Madde 7.2. Gizlilik kararı verilen tezler gizlilik süresince enstitü veya fakülte tarafından gizlilik kuralları çerçevesinde muhafaza edilir, gizlilik kararının kaldırılması halinde Tez Otomasyon Sistemine yüklenir

* *Tez **danışmanının** önerisi ve **enstitü anabilim dalının** uygun görüşü üzerine **enstitü** veya **fakülte yönetim kurulu tarafından karar verilir.***

ETHICAL DECLARATION

In this thesis study, I declare that all the information and documents have been obtained on the base of the academic rules and all audio-visual and written information and results have been presented according to the rules of scientific ethics. I did not do any distortion in the data set. In the case of using other works, related studies have been fully cited in accordance with scientific standards. I also declare that my thesis study is original except for cited references. It was produced by myself in consultation with my supervisor (Assoc. Prof. Hilal DİNÇER D'ALESSANDRO) and my co-supervisor (Prof. Dr. Paul GOVAERTS), and written according to the rules of thesis writing of Hacettepe University Institute of Health Sciences.

Okan ÖZ

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“Our true mentor in life is science.”

Mustafa Kemal ATATÜRK

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ABSTRACT

Öz, O., Assessment of Binaural Benefits in Hearing and Hearing Impaired Listeners, Hacettepe University Graduate School of Health Sciences Audiology Programme Master's Thesis, Ankara, 2023. The primary goal of this study was to investigate which speech material is most appropriate as stimulus in head shadow effect (HSE) and binaural squelch (SQ) tests. The most appropriate speech material was then used to obtain normative values of both tests. The second goal was to explore the results of the HSE, SQ, azimuth localization (LOC), and the Speech, Spatial, and Qualities of Hearing (SSQ) scale in bilateral cochlear implant (CI) users. Study participants consisted of 30 normal-hearing (NH) persons and 34 bilateral CI users. In the first phase of the study, six NHs and 11 CI users underwent both HSE and SQ tests. Tests were done twice with three different speech materials: monosyllabic words (NVA), disyllabic words (BLU), and sentences (LiCoS). In both groups (NH and CI) and for both tests (HSE and SQ), the results for the different speech materials were calculated in terms of (a) effect size; (b) test-retest reliability and (c) inter-individual variability. In the second phase, the speech material selected in the first phase was used to test a further 24 NH participants to obtain normative values for both tests. In the third phase, both tests were administered to a further 23 bilateral CI users who had at least six months of binaural listening experience. In addition to the HSE and SQ tests, the LOC test and the SSQ scale were used. The results of the first phase indicated that BLU and LiCoS were better test materials for HSE and SQ tests compared to NVA. Although BLU and LiCoS revealed similar results in terms of effect size and inter-individual variability, LiCoS was preferred over BLU for the subsequent phases of the study due to its higher test-retest reliability, especially in CI users. In the NH group the mean (± standard deviation) HSE and SQ were 58±14% and 22±11%, respectively. In the CI group, the mean HSE was 49±13% and the mean SQ was 13±14%, and both were significantly lower than those of the NH group ($p<0.05$). There were no statistically significant correlations between the HSE, SQ, LOC, and SSQ results. Further analysis did also not reveal any significant correlations between the test results and demographic variables ($p>0.05$). Sentence tests are preferred as stimulus material in the binaural HSE and SQ tests. Normative data are given for HSE and SQ with the LiCoS sentence test. HSE benefits are positive for all bilateral CI users, while SQ benefits are positive in approximately seven out of ten cases. Because of the high test-retest variability, these tests do not seem suitable for individual evaluations, but should only be used for group comparisons.

Keywords: Head shadow effect, binaural squelch, binaural hearing, cochlear implant, speech audiometry.

ÖZET

Öz, O., Normal İşiten ve İşitme Kayıplı Bireylerde Binaural Faydaların Değerlendirilmesi, Hacettepe Üniversitesi Sağlık Bilimleri Enstitüsü Odyoloji Programı Yüksek Lisans Tezi, Ankara, 2023. Bu çalışmanın birincil amacı, başın gölge etkisi (BGE) ve binaural *squelch* (SQ) testlerinde hangi konuşma materyalinin daha uygun olduğunu araştırmaktır. Sonrasında, uygun olduğuna karar verilen konuşma materyali kullanılarak her iki testin de norm değerleri elde edilmiştir. Çalışmanın ikinci amacı, bilateral koklear implant (Kİ) kullanıcılarında hem bu testlerin hem de azimut lokalizasyon testi (LOK) ve Konuşma, Uzaysal Algı ve İşitme Kalitesi (KUİK) ölçeğinin sonuçlarını incelemektir. Çalışmaya toplamda, 30 normal işiten (Nİ) birey ve 34 bilateral Kİ kullanıcısı katılmıştır. Çalışmanın ilk aşamasında, 6 Nİ ve 11 Kİ kullanıcısına BGE ve SQ testleri uygulanmıştır. Testler üç farklı konuşma materyali ile ikişer kez yapılmıştır: tek heceli kelimeler (NVA), iki heceli kelimeler (BLU) ve cümleler (LiCoS). Her iki grupta (Nİ ve Kİ) ve her iki test için (BGE ve SQ), farklı konuşma materyalleri ile sonuçlar (a) etki büyüklüğü; (b) test-tekrar test güvenilirliği ve (c) bireyler arası değişkenlik açısından hesaplanmıştır. İkinci aşamada, ilk aşamada seçilen konuşma materyali, her iki test için de normatif değerler elde etmek üzere 24 Nİ katılımcıya uygulanmıştır. Üçüncü aşamada, her iki test de en az altı aydır bilateral Kİ kullanan 23 bireye LOK ve KUİK ile birlikte uygulanmıştır. İlk aşamanın sonuçları, BLU ve LiCoS'un NVA'ya kıyasla BGE ve SQ testleri için daha optimal test materyalleri olduğunu göstermiştir. Etki büyüklüğü ve bireyler arası değişkenlik açısından BLU ve LiCoS benzer sonuçlar ortaya koysa da, özellikle Kİ kullanıcılarında daha yüksek test-tekrar test güvenilirliği nedeniyle çalışmanın sonraki aşamalarında LiCoS tercih edilmiştir. Nİ grubunda ortalama (±standart sapma) BGE ve SQ sırasıyla %58±14 ve %22±11 olarak gözlenmiştir. Kİ grubunda ise ortalama BGE ve SQ %49±13 ve %13±14 olarak ölçülmüştür. Kİ grubunun BGE ve SQ skorları Nİ grubuna göre anlamlı derecede düşük olarak gözlenmiştir ($p<0.05$). BGE, SQ, LOK ve KUİK sonuçları arasında istatistiksel olarak anlamlı bir korelasyon gözlenmemiştir. Ayrıca ek analizler de test sonuçları ile demografik değişkenler arasında anlamlı bir ilişki ortaya koymamıştır ($p>0.05$). Sonuçlar, HSE ve SQ testlerinde cümle materyallerinin kullanılması gerektiğini göstermektedir. LiCoS cümleleriyle, HSE ve SQ testleri için normatif veriler elde edilmiştir. Bilateral Kİ kullanıcıları ikinci implantlarından anlamlı bir fayda sağlamaktadır. Bu katkının büyük bir kısmı katılımcıların tamamında BGE tarafından sağlanırken, her 10 katılımcının 7'sinde pozitif SQ binaural işitmeye katkıda bulunmaktadır.

Anahtar Kelimeler: Başın gölgesi etkisi, binaural *squelch*, binaural işitme, koklear implant, konuşma odyometrisi.

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8. APPENDICES

SYMBOLS AND ABBREVIATIONS

A§E	Auditory Speech Sounds Evaluation
APHAB	Abbreviated Profile of Hearing Aid Benefit
BMLD	Binaural Masking Level Differences
CI	Cochlear Implant
CN	Cochlear Nucleus
CV	Coefficient of Variation
CVC	Consonant, Vowel, Consonant
dB	Decibel
DCN	Dorsal Cochlear Nucleus
EAS	Electric Acoustic Stimulation
EaSI	Eargroup Speech Index
HA	Hearing Aid
HF	High-Frequency
HI	Hearing Impaired
HL	Hearing Level
HRTF	Head-Related Transfer Function
HSE	Head Shadow Effect
Hz	Hertz
IC	Inferior Colliculus
ICC	Intraclass Correlation Coefficient
ILD	Interaural Level Differences
IQR	Interquartile Range
ITD	Interaural Time Differences
KEMAR	Knowles Electronic Manikin for Acoustic Research
kHz	Kilohertz
LF	Low-Frequency
LL	Lateral Lemniscus
LOC	Localization

LSOC	Lateral Superior Olivary Complex
MS	Millisecond
MSOC	Medial Superior Olivary Complex
NH	Normal Hearing
PTA	Pure Tone Average
RMS	Root Mean Square
SNR	Signal to Noise Ratio
SOC	Superior Olivary Complex
SPIN	Speech in Noise
SPL	Sound Pressure Level
SQ	Binaural Squelch
SRM	Spatial Release From Masking
SRS	Speech Recognition Score
SRT	Speech Recognition Threshold
SSD	Single-Sided Deafness
SSQ	Speech, Spatial and Qualities of Hearing Scale
SU	Summation Effect
TFS	Temporal Fine Structure
VAR	Variation
VCN	Ventral Cochlear Nucleus

FIGURES

TABLES

1. INTRODUCTION

In most clinical hearing tests, each ear is evaluated separately. Although binaural hearing has numerous benefits, defining and assessing it can be challenging. Furthermore, clinicians are limited to a few tests that give a limited understanding of the true benefits of binaural hearing, and these tests are seldom used in practice. Binaural hearing is usually characterized by six advantages:

1. Head Shadow Effect (HSE): Speech understanding improves when speech is not attenuated by the head.

2. Binaural Squelch (SQ): The ability to understand speech improves when both ears are involved, as central mechanisms improve the signal-to-noise ratio (SNR) when noise is perceived in both ears.

3. Binaural Masking Level Differences (BMLD): The detectability of the target signal improves when the phase of the signal in the ears is changed while the phase of the noise is kept constant.

4. Binaural Summation (SU): Speech understanding with two ears is better than with each ear separately. This effect is attributed to loudness summation.

5. Spatial Release From Masking (SRM): Speech intelligibility improves when noise and signal sources are spatially separated from each other.

6. Localization (LOC): The LOC of the sound source is better with two ears in comparison with one.

Each of these effects can be evaluated by psychoacoustic tests that can be performed in a clinical audiological setting. Due to the lack of standards, there are neither universally accepted test set-ups nor normal values. Moreover, the results of the tests depend on the type of stimulus used (monosyllabic words, disyllabic words, sentences, etc) as well as the type of noise (stationary speech, babble-noise, narrowband noise, etc).

The standardized measures of binaural testing become particularly important in the context of cochlear implants (CI). CI is often the treatment of choice in individuals with severe to profound sensorineural hearing loss. CI results have been well documented. They typically improve speech understanding in quiet to near to normal levels. Speech understanding in noise (SPIN) also improves, though to a lesser extent, while some tasks, such as music perception, localization, etc. remain difficult (1-3). Cochlear implantations were traditionally performed unilaterally, which means that binaural hearing was not restored. This has changed in children, since bilateral implantation has become a common treatment in this population, and it is also getting more common in adults.

In the literature, binaural benefits are generally evaluated utilizing SPIN tests. These methods compare speech understanding in the binaural listening condition with the monaural condition (usually with reference to the better ear). In LOC tests, stimuli are presented in random order through speakers placed at different angles, and the participant is expected to point to the speaker from which the sound comes. In the literature, there are studies showing these benefits in bilateral/bimodal CI users as well as in normal-hearing (NH) people (4-8). Statistical biases in speech recognition tests, which form the basis of binaural benefit assessments, are the main drawback of these studies. Avan et al. (9) quote Dillon’s book (10) in their article: As long as the item lists used in the speech test are not long enough, 10% or more test-retest differences can be observed. A second problem is that in studies reporting significant binaural benefits, results are reported over group averages. However, when the individual results are examined, the amount of difference between the two measurements in many conditions may still not be more than the test-retest variability. Additionally, in most studies in the literature, test-retest reliability of the applied test material is not measured. In fact, it is possible that the variable results reported in different studies in the literature are due to these reasons. By demonstrating the test-retest reliability and establishing norms in these tests, aforementioned problems can be overcome.

The first goal of this study was to investigate which speech material (monosyllabic words, disyllabic words, or sentences) is most appropriate as a stimulus in the HSE and SQ tests. The most appropriate speech material was then used to obtain normative values of both tests.

The second goal was to explore the correlation between HSE, SQ, and LOC in bilateral CI users as well as possible influencing factors, such as the interval between implantations, experience with binaural hearing, etc. Furthermore, a correlation analysis was performed between the results of binaural tests, and the Speech, Spatial, and Qualities of Hearing (SSQ) Scale.

The hypotheses of this study were:

Hypothesis-1) H_0: HSE and SQ test results obtained with different speech materials are not significantly different from each other.

Hypothesis-1) H_1: HSE and SQ test results vary significantly depending on the type of test stimulus.

Hypothesis-2) H_0: HSE and SQ test results in NH individuals do not significantly differ from those of bilateral CI users.

Hypothesis-2) H_1: HSE and SQ test results in NH individuals differ significantly from those of bilateral CI users.

Hypothesis-3) H_0: There is no statistically significant correlation between the test results and the results from the SSQ scale.

Hypothesis-3) H_1: The correlation between the test results and the SSQ is statistically significant.

2. LITERATURE

2.1. Binaural Hearing

Binaural hearing can simply be defined as listening with both ears. Using stereoscopy as an example, Avan et al. (9) explain stereophony as follows: “Similar to stereoscopy, stereophony is based on combining information in the brain from the two ears, creating a robust illusion that confers the stimulus a special character of perspective known as three-dimensional (3D) depth and localization. Both in the visual and auditory modalities, this character contributes to creating 'objects', which are easier to segregate and identify than what would have happened if a single receiver had been available”.

Binaural hearing improves speech understanding and LOC, particularly in the presence of background noise (5, 11-13). Binaural hearing also provides clues about the dimensions of the auditory environment and the perception of reality (14). Localization, the ability to locate the sound source, is crucial in daily life in determining the location of the target signal. The development of localization skills in evolutionary processes was driven by the need to determine the location of prey and predators (15).

It is also essential to be able to understand SPIN since this reflects the challenging listening environments we encounter in everyday life. They are typically classrooms or playgrounds for children, while for adults, they are restaurants, meeting rooms with many speakers, etc. In such environments, signal and noise are often spatially separated from each other. In such cases, when both ears contribute to hearing, the central auditory system integrates information from both ears so that the brain can segregate the talkers from competing sounds. As a result, it becomes easier to understand speech in the presence of background noise (16).

The main contributors of binaural hearing are the acoustic cues derived from the interaural level (ILD) and interaural time differences (ITD) when the sound source is located outside of the median plane (17-20). According to Rayleigh’s (21) duplex theory, ILD cues are found in high-frequency (HF) (>1500 Hertz [Hz]) signals, while

ITD cues are available in low-frequency (LF) signals. ITD cues are not found at HFs because auditory nerve fibres cannot encode the temporal fine structure (TFS) of HF stimuli (9). In many studies, the presence of ITD was shown to improve speech recognition thresholds (SRT) (22-26). Aronoff et al. (27), however, showed that speech understanding in NHs was not dominated by either ILD or ITD cues and that both contributed to speech understanding equally.

Interaural differences heavily depend on the position of the sound source relative to the listener, the speed of the sound, and the size of the head. Interaural differences are not present when signals are coming from a source at 0° azimuth, and the largest differences are found when the source is located at 90° azimuth (17). Abbagnaro et al. (28) report an ITD of 0.8 milliseconds (ms) at 200 Hz, which drops to 0.6 ms at 1.6 kilohertz (kHz), and remains constant at frequencies above 1 kHz.

It was suggested by Carhart (24) that HSE-induced ILD cues would reduce the ITD-induced binaural benefits. This effect is known as binaural interference (29). Bronkhorst & Plomp (25) confirmed Carhart's (24) theory in their study where the binaural benefit was found to be 3.9-5.1 decibel (dB) SRT when no ILD cues were available and decreased to 2.1-3.4 dB SRT when ILD cues were presented. A recent study by Dieudonné & Francart (26) revealed similar results by demonstrating that the SQ-SU combination, which the researchers defined as binaural contrast, positively correlated with ITD cues and negatively correlated with ILD cues. In the same study, researchers found that presenting ILD information reduced binaural benefits while presenting ITD information always improved them (26).

2.2. Role of the Central Auditory System in Binaural Hearing

Spatial listening is the result of many complex processes that occur in different regions of the peripheral and central auditory systems. The coding of frequency, intensity, and temporal information in the cochlea is the first step of this process. However, the main task in this process is carried out by the central auditory structures.

Lower auditory pathways possess unique cellular properties and microcircuits that allow detailed and high-resolution analysis of physical sound parameters, including the temporal characteristics occurring within the submillisecond range (15). Specifically, Bushy cells in the ventral cochlear nuclei (VCN) play a key role in the binaural pathway, responding faithfully to the TFS of LF stimuli and the envelopes of HF stimuli (15).

Neurons in the dorsal cochlear nucleus (DCN) are specialized in processing spectral information. Combined excitatory (from primary auditory nerve fibres) and inhibitory (derived from type II DCN neurons) inputs cause the type IV neurons of DCN to show significant sensitivity to notches in the acoustic spectrum (30, 31), which is crucial in vertical localization.

The superior olivary complex (SOC) in the brainstem is the first place where information from the two ears converge. The information encoded in both cochleae is exploited here. The SOC consists of two parts: Lateral SOC (LSOC) and Medial SOC (MSOC).

ILD information in HF stimuli is processed in LSOC (9). These neurons are excited by input from spherical bushy cells in the ipsilateral cochlear nuclei (CN) and inhibited by input from globular bushy cells in the contralateral CN (15, 32, 33). In this way, neurons become sensitive to differences in intensity between the ears.

When processing ITD information, neurons must resolve time differences between the sound's arrival at each ear, which is almost twice as short as the duration of action potentials carrying this information (15). In MSOC, ITD sensitivity is achieved by bilaterally excited (EE) neurons, while in LSOC it is processed by excitation of neurons in one ear and inhibition in the other (IE) (15). However, researchers showed that MSOC is the primary structure for ITD processing and that reduced localization and ITD sensitivity are observed in cats with atrophy in the MSOC neurons (15, 34-36). MSOC neurons act as binaural coincidence detectors and discharge when signals from both ears are simultaneous (9). The LF neurons here respond to pure-sound stimuli with a phase-locked discharge pattern and are sensitive to the TFS of the sound (15, 37-41).

Outputs of the SOC target the dorsal nucleus of the lateral lemniscus (LL) and the inferior colliculus (IC) (42, 43). IC is a synaptic station for nearly all ascending pathways (15). The IC appears to process all-acoustic cues and filter them into separate streams, laying the groundwork for object recognition at the next synaptic levels in the thalamic-cortical system (15). Type O neurons in the IC show a similar excitation pattern as type IV neurons of DCN when stimulated by narrowband stimuli. However, they show an opposite pattern to a broadband stimulus containing a spectral notch (15, 44). It was suggested that spectral features generated by the head-related transfer function (HRTF) are uniquely processed by the pathway from type IV neurons in the DCN to type O neurons in the IC (15, 44).

Each brain hemisphere has a variety of spatial channels with relatively broad tuning that helps to identify the location of the source (15). However, the brain may have difficulty integrating information from both ears in asymmetrical hearing losses or in bimodal users where the information in both ears is processed differently (9).

2.3. Binaural Benefits

The assessment of spatial hearing is crucial since it is a measure of how well the auditory system is capable of integrating information from both ears (45). Binaural benefits measured in the literature include HSE, SQ, BMLD, SU, SRM, and LOC.

2.3.1. Head Shadow Effect

In dichotic listening, diffraction caused by the head changes the SNR in both ears when noise and signal are spatially separated (17). In such a situation, the head acts like a barrier against the signals coming from the contralateral side and reduces the intensity of the incoming sound, especially at HFs. As a result, when one ear is close to noise, the other ear has a higher SNR. For example, individuals with single-sided deafness (SSD) can benefit from this phenomenon when the noise is on the deaf side. An NH person, on the other hand, will have an increased SNR in one ear anyway. This effect is, however, purely physical. Binaural processing is not needed for HSE and this process is not influenced by central auditory processing (46, 47). However, to use this physical advantage, brain can change the focus directly to the ear with better

SNR (48). According to Laszig et al. (49), this phenomenon can be advantageous, especially in environments such as cars, theatres, dining tables, and meeting rooms where people cannot easily change their surroundings.

HSE is a frequency-dependent phenomenon. HSE is most prevalent at frequencies above 1500 Hz. The reason for this is that HF sounds have shorter wavelengths than the size of the head. Therefore, the intensity of HF sounds decreases more than that of LF sounds. HSE can reduce sounds above 1 kHz by 15-20 dB, and LFs by 3-6 dB (17, 28, 48, 50).

Depending on how the head is positioned in relation to noise and signal sources, HSE may affect speech understanding differently (51). For example, HSE would lead to a disadvantageous situation for the ear contralateral to the speech. Contrariwise, if the noise is coming from a side, HSE will place the contralateral ear in an advantageous position (51).

HSE is usually calculated by subtracting the speech recognition scores (SRS) or the SRT obtained in bilateral condition from the one obtained in unilateral condition, with the signal coming from 0° azimuth and noise from one ear side (±90° azimuth). HSE can also be calculated in a test setup where noise and signal locations are switched (noise in front and signal from one of the sides). But in any case, the second ear added in the bilateral condition is always the one with higher SNR (12, 52).

Although relatively few, there are also studies evaluating monaural HSE (5, 7). In this method, HSE is calculated by subtracting the unilateral score obtained when the noise is on the contralateral side from the SRT obtained when the noise is on the ipsilateral side. In such a setup, ITDs have no significance, since HSE only results from ILDs (26).

In the literature, HSE varies between 8.9 – 10.7 dB SRT in individuals with NH (25, 51).

2.3.2. Binaural Squelch

Squelch as a term was first used by Koenig (53) to describe "the difference between best ear performance and binaural performance". SQ is the overall improvement in speech understanding in the presence of background noise as the second ear becomes available (50). This is accomplished by processing the timing, amplitude, and spectral differences between brainstem nuclei in both ears (48). In the brain, noise and signal can be more clearly processed when they come from both ears; therefore, it may be easier to distinguish these two types of stimuli. In other words, the central auditory system can partially reduce the effect of noise in one ear by using the noise information on the other ear and thus improve the central representation of the information coming from the ear with good SNR (54). Proper integration of information from both ears is needed for SQ. Therefore, SQ requires a certain amount of listening experience and central processing (52).

SQ is predominantly an ITD-dependent effect. Accordingly, Bronkhorst & Plomp (25) found that SQ was not present in patients when ITD cues were not available. It was also shown in the same study that there is a positive correlation between SQ and ITD cues (25). Similarly, Dieudonné & Francart (26) found that SQ exceeded SU when both ILDs and ITDs were present, but the performance fell behind SU when only ILDs were available.

SQ effect is remarkable since the increase in speech understanding is achieved by adding an ear with a lower SNR. Nevertheless, the addition of the second ear also provides additional redundancy, even though it has a relatively low SNR. Therefore, Dieudonné & Francart (26) propose that SQ must be greater than SU to result from interaural differences that lead to binaural processing. According to them, SQ advantage arises from redundant information and not from interaural differences if SQ is below or equal to SU (26).

SQ evaluation typically involves the signal being presented from the front, while the noise comes from ±90° azimuth. Contrary to the HSE assessment, the added ear in the bilateral condition is the one ipsilateral to the noise, therefore with a lower SNR (51).

In the literature, SQ ranges between 2 – 4.9 dB SRT in individuals with NH (25, 51, 55, 56). In test setups conducted at fixed SNRs, SQ effect amounts to 26% speech understanding for those with NH (57).

2.3.3. Binaural Masking Level Differences

BMLD was first described by Licklider (58) and Hirsh (59) as an increase in the detectability of the target signal when the phase of the signal in the ears is changed in the presence of background noise. Even though the underlying mechanisms are not completely understood, it is well established that LF ITDs have a strong influence on BMLD (20).

BMLD assessment involves determining a threshold in the presence of narrowband noise and signal in both ears at the same frequency and phase. Then, the phase of the signal in one ear is changed by 180°. In this way, the signal becomes easier to detect. The improvement in the threshold by inverting the phase of the signal in one ear is called BMLD, and it goes up to 15 dB, especially in LF tones, and it is around 3 dB at 1500 Hz and above (60, 61).

2.3.4. Binaural Summation

In diotic listening, where identical signals are presented to both ears, the brain combines information from both ears to create a stronger representation of the signal compared to monaural listening (49). Here, the ITD and ILD cues are not present, as the signals reaching the ears are the same. Therefore, SU performance is not frequency-dependent (20). According to Dieudonné & Francart (26), SU works like an internal noise cancellation, which occurs as identical information in both ears is summed up.

Binaural summation and redundancy are often used interchangeably. Redundancy, however, requires binaural processing while summation is simply the result of a louder perception of signal intensity (49). Dieudonné & Francart (26), proposes using the term redundancy instead of summation. According to the researchers, the term redundancy focuses on the cue used in this effect (redundant information) rather than speculating about the underlying mechanism (summation of signals) (26). However, in recent studies, mostly the term summation is used and it is meant that binaural processing is also involved (46).

Loudness perception created by a sound in the central auditory system depends on the amount of action potentials in the stimulated auditory neurons (9). According to the work of Fletcher & Munson (62), a double increase in loudness perception requires a 10 dB increase in sound intensity. However, this value decreases at lower intensities. Since a better representation of the signal in the brain is created in the case of binaural hearing, the auditory system also becomes more sensitive to changes in auditory stimuli, and just-noticeable differences in intensity and frequency information improve (9).

SU is typically calculated by comparing the scores obtained with both ears with those obtained with only one ear when both signal and noise are present in the front (5). However, the measurements can also be done in quiet, without noise (63).

In the SU test, one must distinguish between true binaural SU and better ear effect, if the better ear constitutes the added ear in the bilateral condition. In such a case, even if the scores improve in the bilateral condition, the ultimate result will not be better than the result obtained with the better ear alone (27). SU varies between 1.1 – 3 dB SRT in individuals with NH (25, 56, 57, 64).

2.3.5. Spatial Release From Masking

SRM refers to the improvement in the performance when the noise and signal sources are spatially separated from each other relative to the situation where they are co-located (4, 27). As an example, in case noise and signal sources are co-located and their intensities are equal, the noise would mask the signal. However, separation of the signal and the noise would result in a release from masking, which means the signal becomes audible again since one of the ears would have a higher SNR depending on the new location of the sources.

Different mechanisms are thought to contribute to SRM (65). According to Aronoff et al. (27), it is a combination of HSE and SQ. Alternatively, Dieudonné & Francart (26) suggest that SRM is a linear combination of HSE, SQ, and SU. In contrast, Gifford et al. (66) and Sheffield et al. (63) argue that SRM originates from HSE alone where binaural processing is not required. The similar SRM values documented in children with bilateral and unilateral CIs support the argument that SRM does not necessarily require binaural processing (67). As opposed to this, Dieudonné & Francart (26) found that reduction in SU also reduced SRM and that SRM is a function of both ILD and ITD, suggesting that binaural processing may play a role in SRM as well. In 2013, Glyde et al. (68) investigated the association between ITD and ILD cues and SRM. Researchers tested 12 participants in ITD-only, ILD-only, and ITD + ILD conditions. The results showed that ITD-only condition caused significantly less SRM than the combination of ITD + ILD. In contrast, there was no difference between the ILD-only condition and ITD + ILD. Similarly, ITD-only was worse than ILD-only. In summary, the presence of any of the cues was sufficient for SRM up to a certain point, but the SRM achieved by ILD cues was significantly greater than those achieved by ITD cues (68). In a study investigating the effect of LF residual hearing on SRM, Williges et al. (69) demonstrated that SRM was higher in simulated CI users with LF residual hearing than those without residual hearing.

Based on the type of noise used, SRM can vary from 3.6 to 18.4 dB SRT in NH adults (70) and from 3 to 11 dB SRT in NH children (71, 72). Here, informational maskers produce a significantly higher SRM than energetic maskers (70). According to Kidd et al. (73), binaural processing contributes significantly to SRM when an informational masker is present, whereas this contribution is much less for energetic maskers.

2.3.6. Localization

The ability to locate sound sources is called localization, which is another crucial advantage of binaural hearing. One ear might be sufficient for identifying whether the sound source is located on the right or left side, so-called lateralization. However, ITD and ILD cues must be available for a true horizontal LOC (74). An individual with NH is able to locate the sound source in the horizontal plane with an accuracy of 1-2° (15). Typically, the azimuth LOC test involves presenting a series of broadband stimuli (speech noise, broadband noise, or pink noise) in random order from a number of speakers (usually between 7 and 11) and asking the patients to point to the speaker they think the sound is coming from. In many studies, LOC was evaluated in silence, but there are some reports in which the tests were conducted in the presence of background noise. For example, Agrawal et al. (75) created a test setup imitating the cocktail party effect and evaluated the LOC in bilateral CI users by presenting speech stimuli in both quiet and in the presence of background noise. In the absence of background noise, the results of bilateral CI users were comparable to those of NHs. However, significant differences were observed between the groups when background noise was present (75).

Vertical LOC is more complex than horizontal LOC. To locate sound sources in the vertical plane, the auditory system analyses the phase and the magnitude of sound energy across different frequency bands, through frequency-specific modifications in the coming signal (15). The function that identifies these spectral modifications is known as HRTF. This information is largely derived from the direction-specific attenuation in certain frequencies caused by the pinna and concha (15). As a result of diffraction due to the head and pinna, notch-like patterns are perceived in the sound spectrum that provide vertical LOC information. The exact frequency and magnitude information of these notches shifts in elevation (15, 76). For HFs, scattering from the pinnae's complex folds depends on the sound's orientation (29). Using the details of the spectral profiles created in each ear listeners can determine the vertical direction of a sound source (29). NH individuals can localize sound sources in the vertical direction with a resolution of 4° (77).

In a reverberating room, sound waves propagate in different directions and are then reflected from nearby objects and surfaces. This results in the auditory system perceiving both the original sound coming directly from the source and its reflections. Litovsky et al. (78) describe these reflections as "attenuated, sometimes spatially separated, delayed and coherent copies of the originating sound". If the delay between the first sound and its reflection is short enough (<5ms) and the two sounds are equal in volume, the listener will perceive these two sounds as a single image (78). This process is known as binaural fusion.

Between 1-5 ms, although the single image is preserved, the first sounds coming from the source itself are predominant in the LOC of the sound source. This is called LOC dominance or precedence effect (79). Thanks to the precedence effect, only the first sound's information is used, and the reflected sound only influences loudness, timbre, and spatial width, but phase information is completely ignored (9, 29). It is controversial to what extent the precedence effect derives from binaural processing. In many aspects of the precedence effect, studies have not observed a difference between binaural and monaural situations (78), even though Blauert (19) states that this phenomenon originates from binaural processing. In addition, it was shown that hearing loss and aging negatively affect the precedence effect (80).

Reflected sound is perceived as a separate echo in environments with a long reverberation time, such as a hall or train station (29). The point at which the perception of a single image disappears and sounds are perceived as two separate stimuli is known as echo threshold (19, 78, 81). Echo thresholds vary between 5-50 ms in different studies, depending on the stimulus type. In other words, when there is a difference of 5 ms or more between the first sound and the reflected sound, the brain perceives the second sound as an echo. With brief stimuli like clicks, the thresholds are around 5-10 ms, while with long stimuli like noise or speech, the thresholds are as high as 50 ms (82-84).

2.4. Restoration of Binaural Hearing

Even those with hearing loss can benefit from binaural hearing, albeit partially. Individuals with bilateral severe-to-profound hearing loss can benefit from bilateral cochlear implantation. With a cochlear implant in one ear and residual hearing in the other, binaural hearing can be achieved with the combination of a cochlear implant and a hearing aid (HA). This is known as bimodal hearing (54).

2.4.1. Bimodal Hearing

Bimodal stimulation in hearing-impaired (HI) people is a common practice to achieve binaural hearing. Bimodal stimulation is a combination of two different types of stimulation. A typical bimodal application in CI users combines acoustic stimulation delivered by a HA in one ear with electrical stimulation delivered by the CI in the other ear.

Cochlear implantation was formerly used only for individuals with profound or total hearing loss. Individuals with this degree of hearing loss were also less likely to have a residual hearing in their contralateral ears. In recent years, however, the number of bimodal users has increased due to the changes in CI candidacy criteria which allowed people with severe hearing loss to get a CI while still having a residual hearing in the contralateral ear (54, 85-87).

Research has repeatedly demonstrated that bimodal stimulation improves speech understanding and binaural hearing (85, 88-91). Nevertheless, results vary widely among individuals. This variation may be a result of the evaluation methods, duration of HA and CI use, residual hearing on the HA side, and frequency-to-electrode mapping on the CI side (91). Moreover, these variable results may be a consequence of HA fittings that are incompatible with CI. Accordingly, Ching et al. (87) report significant improvements in binaural hearing after fine-tuning the HAs in their contralateral ears in children with CI.

During a conversation, LF information conveys the fundamental frequency of a speaker's voice (74, 92). This is particularly important for the segregation of voices and speech understanding in noisy environments (74). On the other hand, HF stimuli convey important information about the manner and place of consonant articulation (93). The greatest advantage of bimodal hearing, in theory, is increased sound quality, speech, and music perception due to the complementary mechanisms of two different stimuli. The inputs in the LF spectral regions are acoustically processed by HA and combined with the electrical stimulation processed by CI in the HF regions. In some cases, however, stimulating the brain with two different types of stimuli may lead to poorer outcomes. This is mainly due to timing and loudness inconsistencies between CI and HA, frequency mapping mismatches, and thus the limitation of interaural differences (94, 95). In their meta-analysis study, Schafer et al. (96) found that bimodal users did not significantly benefit from SQ. Among bilateral CI users, the weighted effect size (d) of SQ was reported as 0.37, while it was 0.16 for bimodal users (96). Researchers attributed the relatively low effect size in bimodal users to difficulties in the brain's ability to process and integrate two distinct signals (96). Other studies on bimodal users have reported SQ values varying between 2.6 - 3.6 dB SRT (92, 95).

HSE, SU, and LOC in bimodal users are more robust than SQ. Another meta-analysis study conducted by Schafer et al. (97) found that bimodal listeners had a 14% SU and 17.4% HSE. In their subsequent studies, researchers found no significant difference between bilateral CI and bimodal users in terms of SU effect sizes (d=0.42 and d=0.46, respectively) (96). In the same study, bilateral users had an effect size of 1.26 in HSE, and bimodal users had 0.69.

Children can also benefit from bimodal hearing. In a study with children who received bimodal stimulation, Dincer D'Alessandro et al. (98) found that HSE was 17.1% and SQ was 11.8%. Similar to other studies, HSE was observed in almost all (17/19) participants, while SQ was observed in relatively fewer participants (13/19) (98). In a more recent study conducted on 24 children with bimodal hearing aged between 8-12 years, Lotfi et al. (99) found HSE, SQ, and SU to be 3.13, 1.42, and 2.04 dB SRT, respectively.

Bimodal hearing can also improve LOC and quality of hearing (92, 100, 101). Morera et al. (92) tested six bimodal users for LOC, and the root mean square (RMS) values of the participants decreased to 32.9° with bimodal stimulation, while it was 69.5° in the CI-only situation. In a more recent study by Devocht et al. (95), it was shown that bimodal hearing reduces listening effort and makes sounds less tinny, more voluminous, and less unpleasant than CI alone.

2.4.2. Bilateral CI

In the past, people with bilateral severe-to-profound sensorineural hearing loss received only one cochlear implant. Litovsky et al. (4) cite several reasons for this: a) cost of cochlear implants, b) preservation of the second ear for future technologies, c) the additional risks associated with the second surgery, and d) lack of sufficient knowledge and experience about the benefits of bilateral implantation. Clinicians were even concerned about the potential negative effects of bilateral implantation.

Despite the outstanding contribution of unilateral implantation to speech understanding in silence, users continued to have difficulties in speech understanding and LOC, particularly in noise (4, 102, 103).

In 1988, Balkany et al. (104) reported the first bilateral cochlear implantation. Following that, Green et al. (105) also reported encouraging results about bilateral implantation. Further studies have repeatedly demonstrated the benefits of bilateral implantation with regard to speech understanding and LOC (11, 12, 49, 52, 106-108).

Concerning binaural benefits, HSE has the most robust results in bilateral CI users. Laszig et al. (49), demonstrated that participants in their study had HSE and SU but no significant SQ even six months following the implantation. In summary, the literature indicates that bilateral CI users have an HSE of 4.5 - 7.6 dB SRT, an SQ of 0.9 - 2 dB SRT, and an SU of 1 - 2.5 dB SRT (4, 5, 11-13, 16, 20, 66, 109, 110).

The results of the studies in which the tests were performed at fixed SNRs vary between 22 - 49% for HSE, 1.7% - 18% for SQ, and 4 - 12% for SU (6-8, 12, 20, 49, 111).

It takes most bilateral CI patients 3-12 months to learn how to use binaural cues (108). According to the studies on adult CI users, HSE and LOC become evident three months after the second implantation (49, 52, 108), SU after three to six months (49, 52, 108, 112), and SQ after twelve months (6, 112). However, HSE and SU do not change over time despite their rapid onset, while SQ improves over time (7). In a 4-year follow-up study, Eapen et al. (7) showed that after bilateral simultaneous implantation individuals had an SQ of 8.3% in the first year, 13.1% in the second year, 11.8% in the third year, and 18.1% in the fourth year. SU and HSE, on the other hand, did not change after the 1st year (7).

Benefits of bilateral CI were also demonstrated in studies using subjective assessment tools such as health-related scales/questionnaires (12, 105). Litovsky et al. (4) applied the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire to bilateral CI users. Participants reported that they performed better in challenging listening environments in the bilateral condition compared to the unilateral condition (4). In their study using the SSQ, Laske et al. (113) found similar results too.

Overall, bilateral implantation leads to improved speech understanding in noisy environments. This is mostly due to HSE, but some people also benefit from SQ and

SU. Recent studies have also shown the benefits of binaural hearing in specific groups (66, 114-118). Punte et al. (115) showed that bilateral electric acoustic stimulation (EAS) resulted in a 0.5 dB SRT SU, 1.2 dB SRT SQ, and 3.4 dB SRT HSE. In a study on individuals with single-sided deafness (SSD), Vermeire & Van de Heyning (114) examined the improvements in binaural hearing after implantation. Individuals using HA on their contralateral side experienced a 3.8 dB SRT SQ and a 6.5 dB SRT HSE, while there was no significant SU effect (114). SQ and HSE were 1.2 and 1.7 dB SRT, respectively, for those with NH on the contralateral side. Similar results in patients with SSD were also reported by Arndt et al. (116) and Bernstein et al. (117). Távora-Vieira et al. (1) examined ILD-based LOC in patients with SSD. Participants in the study had an average RMS of 48.9° when CI was off, which dropped to 22.8° when CI was on (1). Similarly, Döge et al. (118) found that patients with SSD had a 12.9° improvement in the azimuth LOC test after implantation. Gifford et al. (66), compared binaural benefits between bimodal users and bilateral CI users with and without LF residual hearing. They found no significant differences in SU and SRM between the groups. In HSE, bilateral CI users without residual hearing performed significantly better than the rest at the fixed SNR of +5 dB, but with the adaptive algorithm, there was no significant difference. In terms of SQ, on the other hand, bilateral CI users without residual hearing performed worse than both groups (66).

Compared to adults, fewer studies have evaluated binaural benefits in children with bilateral CI. Van Deun et al. (119) found that children had an SRM of 3 dB SRT and an HSE of 4 – 6 dB SRT, but did not report SU or SQ. SRM in children was also evident both in studies by Murphy et al. (120) and Nittrouer et al. (67). Furthermore, Nittrouer et al. (67) reported an SU of 10% in silence, which dropped to 3-4% in the presence of background noise. Sheffield et al. (63), however, demonstrated that the second CI does not contribute to SU in silence, but it provides a significant benefit in the presence of background noise. In the same study, HSE, SRM, and SQ were 23.2%, 14%, and 1.1%, respectively. When the signal came from front, and the noise from multiple speakers located around the listener, the performance achieved with binaural hearing was 18.5% better than that with the better ear alone (63). This improvement cannot be attributed to either SQ or SU, but rather to an overall binaural hearing advantage (63). Finally, Galvin et al. (121) found no significant SQ in children who were bilaterally implanted before the age of 4 and had at least two years of binaural hearing experience at the time of testing.

Although there are many different reasons for the variability in the results between individuals, the asymmetry between the ears and the listening experience with electrical stimulation are perhaps the most important ones. Mosnier et al. (122) reported that those with symmetric hearing loss experienced significantly greater binaural benefits than those with asymmetric hearing loss. Asymmetry is generally minimal when CI receivers are implanted early and with a short or no delay in between the implantations. Gordon & Papsin (123) showed that early implantation is associated with greater binaural benefits. A long delay between implantations may lead to larger monaural differences, although these differences may be eliminated to some extent with a prolonged binaural listening experience. Chadha et al. (124) found significant SRM in simultaneously implanted and sequentially implanted children, although the scores of the simultaneously implanted children were closer to those with normal hearing. Additionally, SU was significant in the simultaneously implanted group but was not significant in the sequentially implanted group. Studies with CI users also showed that ITD sensitivity increases with exposure to acoustic hearing at an early age and bilateral electrical stimulation experience after implantation but decreases with aging (125).

The processor and microphone types of an individual may also influence the results. In unilateral CI users with SSD, Kurz et al. (126) showed that the adaptive microphone mode provided better HSE, SQ, and SRM than natural and omnidirectional modes. LOC, however, was better in the omnidirectional mode than in the adaptive mode (126).

3. MATERIALS AND METHODS

This prospective study was conducted in the Eargroup (Antwerp, Belgium) as a thesis for the Audiology Master's Programme at Hacettepe University, Graduate School of Health Sciences. Participants were given information about the study and its purpose, and informed consent forms were obtained from all participants. For participants under 18 years of age, parental consent was obtained in addition to their own. The Ethics Committee of Antwerp University Hospital (UZA) approved the study on 22/10/2021 with the project ID: 2021-0551 - BUN B3002021000155 (see Appendix-1).

This study consisted of three phases:

1. Determining the optimal speech material for HSE and SQ:

Six NH participants underwent both HSE and SQ test. Eleven CI users were also tested, either with the HSE test (N=5) or the SQ test (N=5) or both (N=1). Tests were done twice (to calculate the test-retest difference) with three different speech materials: monosyllabic words (NVA) (127), disyllabic words (BLU) (127), and sentences (LiCoS) (128). In both groups (NH and CI) and for both tests (HSE and SQ), the results for the different speech materials were calculated in terms of (a) effect size; (b) test-retest reliability and (c) inter-individual variability. We envisaged that the best speech list would be characterised by a) a large effect size in the NH group, b) a large test-retest reliability in both the NH and the CI groups, and c) a small inter-individual variability in the NH group. The speech list selected on the basis of these criteria would then be used in the next stages of the study.

2. Obtaining normative data of HSE and SQ:

The optimal speech material selected in the first phase was used to test a further 24 NH participants to obtain normative values for both tests.

3. Assessing the binaural benefits in bilateral CI users:

Both tests were also administered to a further 23 bilateral CI users who had at least six months of binaural listening experience. Besides the HSE and SQ tests, the LOC test and the SSQ scale were also applied.

The second and third phases were carried out simultaneously after the completion of the first phase. More detailed information about the methods used in the consecutive phases will be discussed later.

3.1. Participants

The participants of the study consisted of 34 bilateral CI users aged between 14 and 80 who were being followed in the Eargroup, and 30 NH individuals between the ages of 19 and 39 who did not have a previous history of hearing loss. In the CI group, twelve participants (35%) were implanted postlingually (>4 years of age), while 22 (65%) were implanted prelingually. NH individuals were recruited from students, interns, patients' companions, employees' families, and friends.

3.1.1. Inclusion Criteria

CI Group

- Being older than 12 years old,
- Having minimum six months of binaural listening experience,
- Speaking Dutch as mother tongue,
- Being able to perform psychoacoustic tests.

NH Group

- Being between the ages of 18-40,
- Having hearing thresholds ≤20 dB hearing level (HL) at all the octave frequencies tested between 125 – 8000 Hz,
- Speaking Dutch as mother tongue,
- Being able to perform psychoacoustic tests.

3.1.2. Exclusion Criteria

CI Group

- Having general comorbidities that would not allow participation,
- Being unwilling to participate in the study.

NH Group

- Having a previous history of hearing loss,
- Having general comorbidities that would not allow participation,
- Being unwilling to participate in the study.

3.2. Methodology

3.2.1. Pure Tone Audiometry

Pure tone thresholds were obtained from the participants using the modified Hughson-Westlake down-up procedure (129, 130).

NH participants were tested in a soundproof booth using an Aurical audiometer (Otometrics-Natus Medical Incorporated, California, USA) and a TDH-39P headphone (Telephonics Corporation, New York, USA). Prior to testing, the transducer was calibrated using a 6cc acoustic coupler and a BSWA 308 Type 1 sound level meter (BSWA Technology, Beijing, China).

CI users were tested in Free Field condition using Otocube (Otoconsult NV, Antwerp, Belgium). Otocube is a portable desktop box that replaces classic soundproof booths in the testing of CI patients. Otocube has a built-in loudspeaker which allows delivering the stimuli to the patient's sound processor in isolation from the external environment.

Before testing in the Otocube, a long coil cable was first connected to the sound processor. The sound processor was then placed in the Otocube as shown in Figure 3.1.

Figure 3.1. Portable desktop box (Otocube) used in audiometric examinations of CI users.

The Auditory Speech Sounds Evaluation (A§E) psychoacoustics test suite (Otoconsult NV, Antwerp, Belgium) was used to deliver the test stimuli through a computer connected to the Otocube (131). Otocube calibration before the testing was performed using Otocube Monitor Tool (Otoconsult NV, Antwerp, Belgium).

3.2.2. Speech Audiometry in Quiet

Prior to the HSE and SQ tests, speech in quiet test in CI users was performed with their everyday program settings using Flemish monosyllables (NVA) (127). No participant had a program with an active directional or an adaptive microphone setting. Only the omnidirectional microphone mode was used for the tests. SRSs were obtained by presenting two lists of 12 words at four different levels (40, 55, 70, and 85 dB sound pressure levels [SPL]). The weighted average was calculated using the Equation 3.1.

$$EaSI = \frac{SRS_{40}+SRS_{55}+(2\times SRS_{70})+SRS_{85}}{5} \tag{3.1}$$

where EaSI stands for Eargroup Speech Index and SRS_x stands for phoneme score at the presentation level of “x” dB SPL.

3.2.3. HSE and SQ

Test Setup

The test setup was created using three Fostex 6301NB Personal loudspeakers (Foster Electric Company Ltd, Tokyo, Japan). The speakers were placed at a distance of 1m from the participant, at 0°, +90° and -90° azimuth (Figure 3.2).

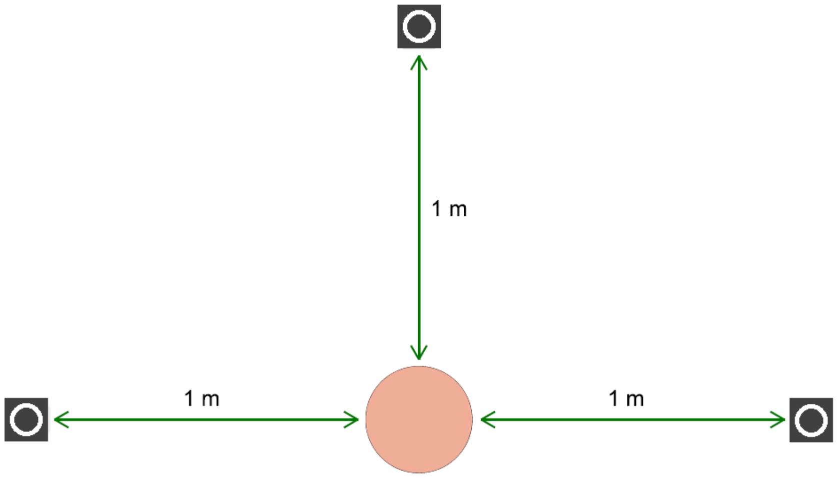

Figure 3.2. HSE and SQ test setup with three speakers at 0°, -90°, and +90° azimuth, each at a 1m distance from the participant.

The speakers were connected to a computer with a Gigaport Soundcard (ESI Audiotechnik GmbH, Leonberg, Germany). The A§E test suite (Otoconsult NV, Antwerp, Belgium) was used to control the stimuli (131). The test room was untreated, and had an ambient background noise level of 30 dB (A) (Figure 3.3).

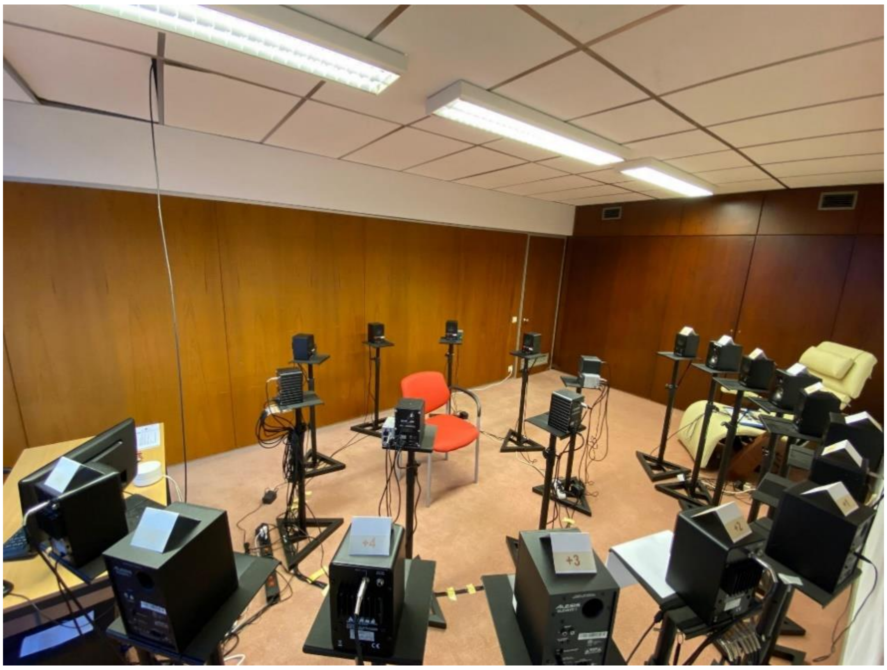

Figure 3.3. Test room where HSE, SQ, and LOC tests were conducted.

Calibration of the loudspeakers before the testing was carried out using the BSWA 308 Type 1 sound level meter with a BSWA MPA 231T free-field microphone (BSWA Technology, Beijing, China).

Test Stimuli

Three different speech materials were used for HSE and SQ tests. These materials were: Flemish monosyllables NVA (127), Flemish disyllabic words BLU (127), and sentences LiCoS (128).

NVA speech material consists of monosyllabic consonant, vowel, consonant (CVC) words. The test contains 15 lists of 12 words each. Each list has a similar set of initial consonants, vowels, and final consonants. NVA lists are ideal for evaluating speech understanding using phoneme scores based on the percentage of correctly identified phonemes (127).

BLU was developed in response to the need for a Flemish speech test based on disyllabic words (127). The test contains 15 lists of 10 spondee words each. Each word has the CVC-CVC structure, and each syllable is a separate existing word. BLU lists are suitable materials for evaluating speech understanding in both quiet and noise based on word scores. Each correct identified word counts for 10%.

As a more representative speech material of modern Dutch, LiCoS (Linguistically Controlled Sentences) was developed by Coene et al. (128). The test material consists of sentences articulated by one female and one male speaker. In LiCoS, there are 12 lists of 30 sentences each with two keywords. Therefore, each correctly repeated keyword corresponds to 50% speech understanding score. The keywords were chosen based on which sentence intelligibility to be assessed (128). LiCoS lists comprise sentences with varying syntactic complexity. Different lists are balanced in terms of various linguistic parameters, including lexical, phonological, morphological, and syntactic components of modern Dutch (128). The lists are also balanced based on the length of the sentences. LiCoS sentences follow the syntactic rules of modern Dutch. However, no fixed expressions or two keywords with the same semantic structure are available in any sentence.

Normative values of the materials are presented in Table 3.1 (127, 128).

Table 3.1. Normative values of NVA, BLU, and LiCoS tests.

Speech Material	SRT (dB SPL)	Slope at SRT (%/dB)
	In quiet	
NVA	19 ± 1.1	4.8 ± 0.7
BLU	23.2 ± 0.9	8 ± 1.4
LiCoS	25.77 ± 2.2	10.2 ± 2.3
	In noise	
NVA	-9.1 ± 0.6	5.5 ± 0.6
BLU	-7 ± 0.6	10.1 ± 1.6
LiCoS	-2.8 ± 0.7	12.9 ± 3.3

Test Principles

HSE and SQ tests were conducted using the A§E psychoacoustics test suite (131).

The test parameters were as follows:

1. Speech material:

SQ and HSE scores were determined by comparing the results of the SPIN tests performed in binaural and monaural listening conditions. Three different types of speech materials (NVA, BLU, and LiCoS) were used for the first phase of the study. Participants who were tested with HSE only, for example, had to do the test six times (2x with NVA, 2x with BLU, and 2x with LiCoS). In each participant's test, the order of the presentation of the speech materials was determined randomly. The retests, however, were always performed in the same order as the first test.

One list from each speech material was played to the participants before the test, and the answers to these lists were not included in the scoring. All subsequent tests used different lists in a random order to minimize any learning effects.

The HSE and SQ tests together took in average 5 to 10 minutes. Since the tests were repeated with three different speech materials, it took a total of 15 to 30 minutes to test a participant with all three materials. All participants took a 10-minute break after the first session. Then, in the second session, the tests were repeated to examine the test-retest reliability. Therefore, the total time required was 40 to 60 minutes for an NH individual. CI users (except one) had a total test time of 25 to 40 minutes because they were tested with only one of the HSE or SQ tests.

Following the study's first phase, the optimal speech material for the HSE and SQ tests was selected. In the following phases, only the speech material selected in the first phase was used.

2. Reference ear ('first ear'):

The reference ear was the ear that was tested in the monaural listening condition. The reference ear of each NH participant was randomly assigned. The right ear was tested in half of the participants, and the left ear in the other half.

3. Locations of the signal and noise:

In the HSE test, noise was presented from the speaker at 0° azimuth, while signal was presented from the second ear (non-reference) side (+ or - 90° azimuth).

In the SQ test, on the other hand, signal was presented from 0° azimuth, while noise was presented from the second ear side.

4. Noise:

Speech-weighted stationary noise was used for SPIN measurements. The noise used for each speech material was constructed from the corresponding words or sentences so that it always had the same long-term average spectrum as the signal (127, 128).

5. Adaptive algorithm:

Both the SQ and HSE tests began by determining an SRT using an adaptive algorithm. The adaptive procedure that was followed in this study was based on the simple up-down staircase method. The parameters of the algorithm are listed in Table 3.2.

Table 3.2. The parameters of the adaptive algorithm used in HSE and SQ tests.

Initial signal level	75 dB SPL
Initial SNR	10 dB SPL
Noise intensity	Fixed (65 dB SPL)
Target	70%
Initial step	10 dB
Minimum step size	2 dB
Stop criterion	After eight reversals
Threshold estimation	Average of last six reversals

Step size was recalculated after each trial based on the following Equation 3.2.

$$s = S_i \times \left(\frac{1}{2}\right)^{\mathrm{R}} \qquad (3.2)$$

where s = step size, S_i = the initial step size and R = number of reversals.

Once an SRT was determined using the adaptive algorithm in the binaural listening condition, the test proceeded to the next step. Here, individuals were tested in the monaural listening condition at the SNR determined in the previous step. For example, if a person had an SRT of +5 dB SPL in the first test, the second test was run at a fixed SNR of +5 dB SPL (signal at 70 dB SPL and noise at 65 dB SPL). Since the SRT determined in the first step corresponded to a 70% correct response, a 60% score in the second test, for example, would indicate a 10% binaural benefit compared to monaural listening. Figure 3.4 and Figure 3.5 show examples of the display of the HSE and SQ test results.

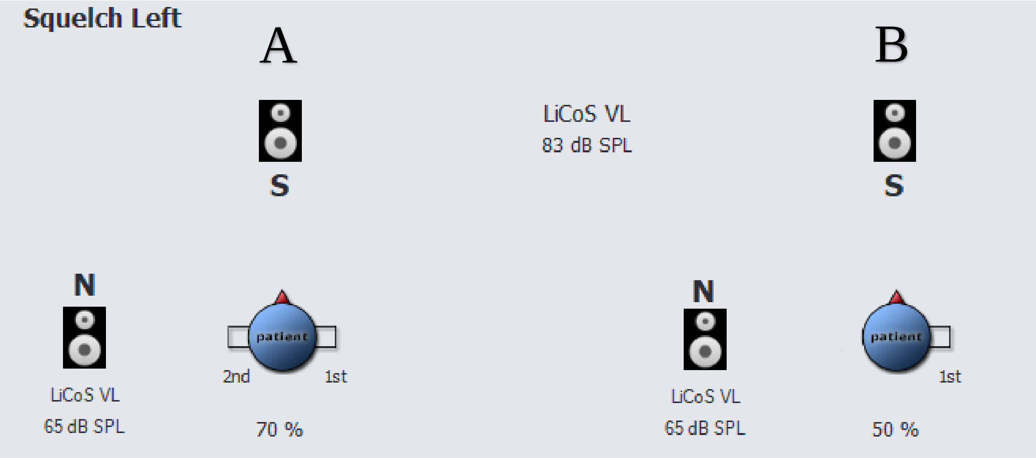

Figure 3.4. A: SQ test with both ears available with the signal coming from front and the noise coming from -90° azimuth when the right ear is selected as the first ear. The SRT obtained at 70% correct response rate in this example is 18 dB SPL (83 dB SPL – 65 dB SPL), **B:** SQ test with only right ear available. The score at 18 dB SNR is 50%, so the SQ = 20% (70% - 50%).

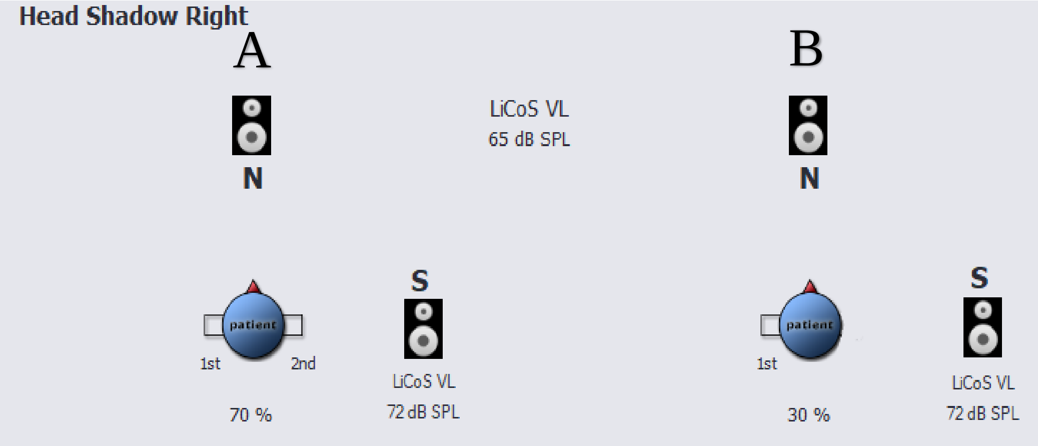

Figure 3.5. A: HSE test with both ears available with the signal coming from +90° azimuth and the noise coming from front when the left ear is selected as the first ear. The SRT obtained at 70% correct response rate in this example is 7 dB SPL (72 dB SPL – 65 dB SPL), **B:** HSE test with only left ear available. The score at 7 dB SNR is 30%, so the HSE = 40% (70% - 30%).

CI users were asked to turn off their second implanted device in the monaural listening condition. The non-reference ears of the NH group were blocked with E-A-RTone 3A insert earphones (Aearo Technologies LLC, Indiana, United States) and masked via Madson Itera II audiometer (Otometrics-Natus Medical Incorporated, California, United States), with a 60 dB HL broadband speech noise. The insert earphones were calibrated prior to testing using a 2cc acoustic coupler.

3.2.4. Azimuth Localization

Azimuth LOC test was carried out using seven Fostex 6301B loudspeakers (Foster Electric Company Ltd, Tokyo, Japan). This test was performed in the same room used for HSE and SQ tests, using the same software but with different loudspeakers. The test stimulus was speech noise presented at 70 dB SPL. A ±3 dB level rove was applied to compensate for any additional cues caused by the characteristics of the loudspeakers.

In the test, speakers were numbered from -3 (left side) to +3 (right side). The loudspeaker -3 was at -60° azimuth, while the loudspeaker +3 was at +60° azimuth. Each speaker was thus at a 20° angle from the other. Figure 3.6 illustrates the test setup.

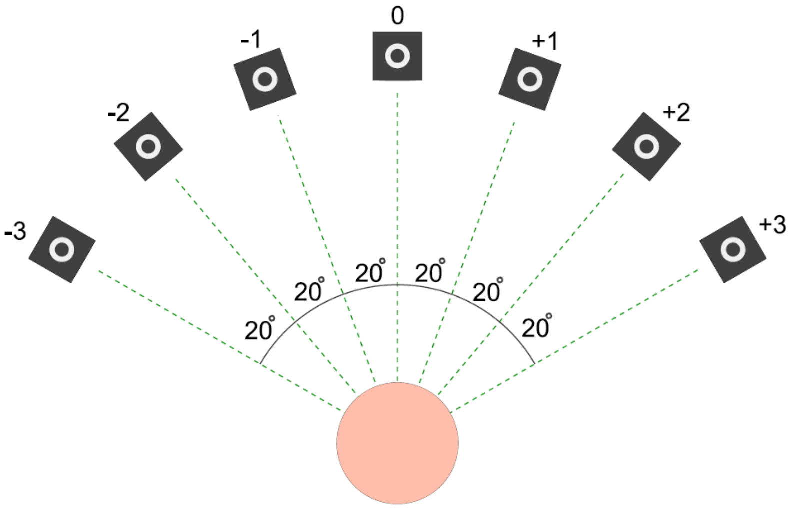

Figure 3.6. Azimuth localization test setup, with seven loudspeakers each at a 20° angle from the other.

Participants received a short training before starting the test. In the test, stimuli were presented from seven different speakers in random order, and individuals were asked to point to the speaker from which they heard the sound. The stimulus was presented five times from each speaker, and at the end of the test, two results were available: RMS and variation (VAR).

The RMS represents the mean test error. An RMS value close to zero indicates good LOC ability. The RMS was calculated as the root mean square of the differences between median response and normal response for all speakers (Equation 3.3)

$$RMS = \sqrt{\frac{\sum_{S=1}^{N}(Rs - NORMs)^2}{N}} \qquad (3.3)$$

where Rs = the median response for Speaker S, N = the number of speakers, and norm = the normal value for Speaker S.

VAR indicates the consistency of patient responses. A lower VAR indicates more reliable responses. The VAR was calculated as the average of the absolute value of differences between each score and the corresponding median score for all speakers (Equation 3.4). The test results with a VAR value above 20° were excluded from the statistical analysis.

$$VAR = \frac{\sum_{response=1}^{N} ABS(response - median)}{N} \qquad (3.4)$$

where ABS = absolute value, N = the number of responses.

3.2.5. SSQ Scale

Gatehouse and Noble (132) developed the SSQ Scale to meet the need for a subjective self-assessment tool for speech understanding, spatial hearing, and qualities of hearing. The original scale consisted of 49 questions. In 2013, Noble et al. (133) developed a 12-item version of the SSQ (SSQ12) which was later translated into Flemish by KU Leuven University. In the present study, the SSQ12 was used since it is more time-efficient than the SSQ49.

In this scale, respondents rate their own performance on each item from 0 (not at all) to 10 (perfect). Higher scores always indicate a greater ability since none of the items are worded in a negative direction.

3.3. Statistical Analysis

Descriptive statistics were used to summarize the data. Tables and graphs were created using Microsoft Excel for Microsoft 365, version 2201 (Microsoft, Redmond-Washington, United States). The independent-samples t-test or Mann-Whitney U test, depending on whether parametric test assumptions were met, was used to compare differences between two independent groups. One of the Pearson or Spearman coefficients was used for correlation analysis. The Shapiro-Wilk test was used to test for normality. The significance level was set at 0.05. IBM SPSS Statistics for Windows, Version 20.0 (IBM Corp., Armonk-New York, United States) was used for data analysis.

At the end of the first phase, the following data were available for each speech material: a) test results (effect values); b) test-retest results and c) inter-individual variability. The optimal speech material was chosen based on a) the greatest effect size in NHs, b) the greatest test-retest reliability in NHs and CIs, and c) the smallest inter-individual variability in NHs.

The Kruskal-Wallis test was used to compare the effect sizes for three different speech materials. During the analysis, only the first results from each speech test were used. Retest results were not taken into account in this analysis. In case where a statistically significant p-value could not be obtained, the decision was made on the basis of descriptive statistics.

Test-retest reliability was calculated using two-way mixed Intraclass Correlation Coefficient (ICC). ICC is a widely used reliability index in test-retest analysis (134, 135). ICC has advantages over other methods that can be used for test-retest analysis such as Paired t-test and Pearson correlation. For example, the Paired t-test is a method for analyzing agreement between two measurements, and Pearson correlation is a way to measure correlation that does not take systematic differences into account. ICC however, reflects both degree of correlation and agreement (134). ICC values less than 0.5 indicate poor reliability, those between 0.5 and 0.75 indicate moderate reliability, those between 0.75 and 0.9 indicate good reliability, and those greater than 0.9 indicate excellent reliability (134-136).

Inter-individual variability was calculated using the coefficient of variation (CV). The CV shows the extent of variability of data in a sample independently of the unit of the measurement (137). It is calculated by dividing the standard deviation by the mean.

4. RESULTS

A total of 64 people participated in the study. Thirty of them were in the NH group, and 34 were in the CI group. The NH group consisted of 14 (47%) male and 16 (53%) female participants, with a median age of 23.5 years (Q1: 22 and Q3: 28.5). The hearing thresholds of the participants in the NH group were ≤20 dB HL at all octave frequencies between 125 and 8000 Hz, and the mean pure tone averages (PTA) of the group were 7±4 dB HL in the right ear and 8±4 dB HL in the left ear.

The CI group consisted of 19 (56%) female and 15 (44%) male participants, with a median age of 21 years (Q1: 16 and Q3: 28). Nineteen participants (56%) had their first implant on the right, and 15 participants (44%) had their first implant on the left. None of the participants was implanted simultaneously. The median ages at the first and second implantations were 3 years (Q1: 1 and Q3: 9.3) and 9.5 (Q1: 4.8 and Q3: 23.3), respectively. The participants had an average of 125±67 months of experience with their 2nd CI. On the first CI side of the participants, the mean aided PTA was 18±5 dB HL, while on the second CI side, it was 22±6 dB HL. The median aided EaSI score was 89% (Q1: 79.8 and Q3: 93) with the first CI and 82.5% (Q1: 76.8 and Q3: 89) with the second CI. The PTA and EaSI scores on the 1st CI side were significantly better than those on the 2nd CI side ($p<0.05$).

An overview of the participants included in the CI group is presented in Table 4.1.

Table 4.1. Overview of the participants in the CI group.

P	Age	Gender	Cause of Deafness	1st CI	2nd CI	Age at 1st CI (Y)	Age at 2nd CI (Y)
P1	14	M	Congenital unknown	AB HiRes 90K + Naída Q90	Neurelec Digi SP20 + Neo	6 months	1
P2	15	F	CMV	AB HiRes90K HiFocus 1J + Sky M90	Cochlear CI512 + CP910	3	11
P3	21	F	MYO 15A	Cochlear CI24R (CS) + CP1150	Cochlear CI24R (CS) + CP1150	5 months	1
P4	19	F	Congenital unknown	AB HiRes90K HiFocus Helix + Naída M90	AB HiRes90K HiFocus Helix + Naída M90	4	8
P5	22	M	Congenital unknown	Cochlear CI24R (CS) + CP910	Neurelec Digi SP20 + Neo	2	7
P6	20	M	LVAS	Cochlear CI24RE (CA) + CP910	Cochlear CI512 + CP1000	4	9

Table 4.1. (continued) Overview of the participants in the CI group.

P	Age	Gender	Cause of Deafness	1st CI	2nd CI	Age at 1st CI (Y)	Age at 2nd CI (Y)
P7	26	F	CMV	Cochlear CI24R (CS) + CP1150	Cochlear CI24R (CS) + CP1150	3	6
P8	25	F	Congenital unknown	AB HiRes90K Adv HiFocus ms + Naída Q90	AB HiRes90K HiFocus Helix + Naída Q90	9	13
P9	27	M	Connexine 26	Neurelec Digi SP20 + Neo	AB HiRes90K HiFocus 1J + Naída M90	2	10
P10	16	M	CMV	AB HiRes90K HiFocus 1J + Sky M90	Neurelec Digi SP20 + Neo	7 months	1
P11	23	M	Congenital unknown	AB HiRes90K HiFocus Helix + Naída M90	Cochlear CI24M + CP1000	1	2
P12	21	F	Connexine 26	Cochlear CI24M + CP910	ESP Neurelec Digi Saphyr	6 months	4
P13	16	M	Congenital unknown	AB HiRes 90K HiFocus Helix + Naída Q90	AB HiRes 90K Adv MS + Naída M90	3	11
P14	15	F	Connexine 26	Neurelec + Neo	Neurelec Digi SP + Neo	10 months	4
P15	20	M	LVAS	Cochlear CI24R (CS) + CP1000	Cochlear CI512 + CP1150	2	9
P16	42	F	Congenital unknown	AB HiRes90K HiFocus Helix + Naída M90	AB HiRes90K HiFocus ms + Naída Q70	32	34
P17	16	M	IP-2	Cochlear CI24RE (CA) + CP1000	Cochlear CI24RE (CA) + CP1000	1	2
P18	50	M	Rubella	AB HiRes 90K + Naída Q90	AB HiRes Ultra 3D ms + Naída Q90	41	48
P19	30	M	Congenital unknown	Cochlear CI24RE (CA) + CP1000	Cochlear CI24RE (CA) + CP1000	23	24
P20	25	M	Connexine 26	Cochlear CI24RE (CA) + CP910	Cochlear CI24RE (CA) + CP910	10	12
P21	64	F	Mumps	Med-El Concerto Flex28 + Sonnet	Neurelec Digi SP20 + Neo	55	58
P22	19	F	Connexine 26	Cochlear CI422 + CP1150	Cochlear CI512 + CP1150	1	8
P23	24	F	Congenital unknown	Cochlear CI24R (CS) + CP1000	Cochlear CI622 + CP1000	4	23
P24	20	F	Connexine 26	Cochlear CI612 + CP1000	Neurelec Digi SP20 + Neo	2	5
P25	15	F	Congenital unknown	AB HiRes90K HiFocus Helix + Sky M90	AB HiRes90K HiFocus Helix + Harmony	3	5
P26	29	F	Congenital unknown	Cochlear CI24R (CS) + CP1000	Cochlear CI622 + CP1000	8	28
P27	80	M	COCH (DFNA9)	AB HiRes90k Hifocus 1J + Naída Q90	AB HiRes90k Ultra HiFocus ms + Naída Q90	64	76
P28	26	M	CMV	AB HiRes90K HiFocus 1J + Naída M90	AB HiRes90K HiFocus Helix + Naída M90	8	15
P29	37	F	Progressive unknown	Cochlear CI522 + CP910	Cochlear CI622 + CP1000	32	35
P30	56	F	Congenital unknown	Cochlear CI512 + CP910	Cochlear CI24RE (CA) + CP1000	34	46
P31	14	M	Congenital unknown	Cochlear CI522 + CP1000	Cochlear CI532 + CP1000	8	10

Table 4.1. (continued) Overview of the participants in the CI group.

P	**Age**	**Gender**	**Cause of Deafness**	**1st CI**	**2nd CI**	**Age at 1st CI (Y)**	**Age at 2nd CI (Y)**
P32	20	F	Congenital unknown	Neurelec Digi SP20 + Neo	Neurelec Digi SP20 + Neo	2	6
P33	15	F	Congenital unknown	AB HiRes90K HiFocus 1J + Naída Q90	Neurelec Digi SP20 + Saphyr Neo	10 months	1
P34	17	F	ANHD	AB HiRes90K HiFocus 1J + Sky M90	AB HiRes90K HiFocus ms + Sky M90	4	11

AB, Advanced Bionics (Stäfa, Switzerland); Med-El (Innsbruck, Austria); Nucleus, Cochlear (Sydney, Australia); Digisonic, Oticon Medical (Smørum, Denmark).
ANHD, auditory neuropathy spectrum disorder; CMV, cytomegalovirus; F, female; IP, incomplete partition; LVAS, large vestibular aqueduct syndrome; M, male; P, participant; Y, year.

4.1. Optimal Speech Material for HSE and SQ

4.1.1. Effect Size

Both for the HSE and SQ tests, the BLU and LiCoS test results were higher than those of the NVA, although the differences were not statistically significant (p>0.05).

Figure 4.1 and Figure 4.2 illustrate the distribution of the results in box plots. Table 4.2 and Table 4.3 present the descriptive statistics for the results.

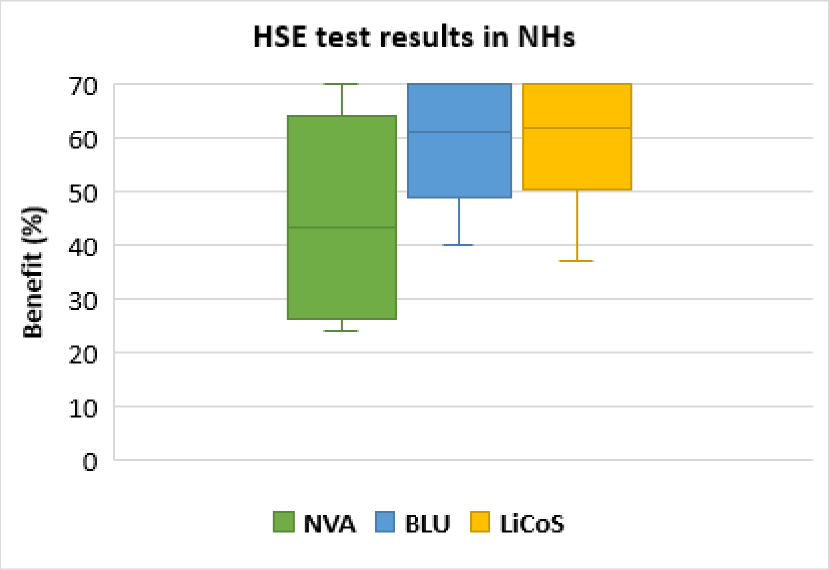

Figure 4.1. Box plots of the HSE test results in NH individuals for NVA, BLU, and LiCoS speech materials.

Table 4.2. Descriptive statistics of the HSE test results in NHs.

Descriptive Statistics	NVA	BLU	LiCoS
		HSE (%)	
Min	24	40	37
Q1	26.3	49	50.5
Median	43.5	61	62
Q3	64	70	70
Max	70	70	70
IQR	37.8	21	19.5

Min, minimum; Q1, first quartile; Q3, third quartile; Max, maximum; IQR, interquartile range.

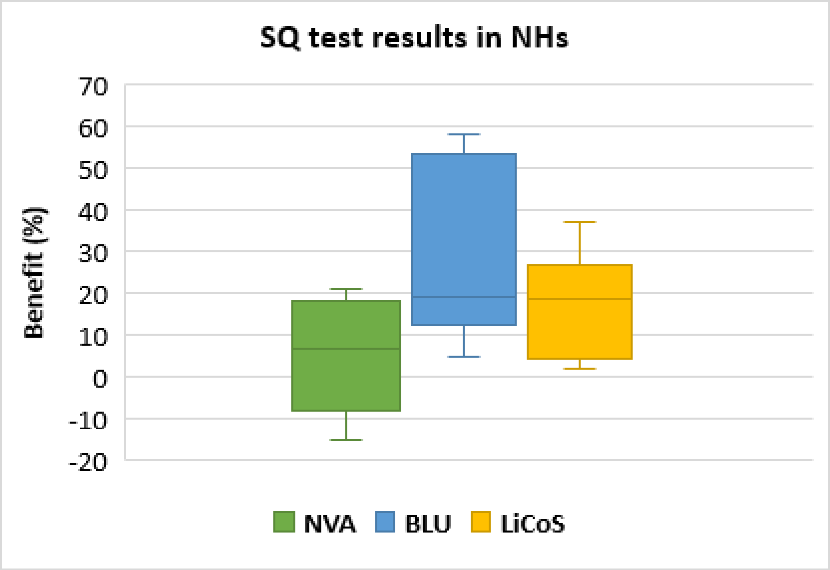

Figure 4.2. Box plots of the SQ test results in NH individuals for NVA, BLU, and LiCoS speech materials.

Table 4.3. Descriptive statistics of the SQ test results in NHs.

Descriptive Statistics	NVA	BLU	LiCoS
		SQ (%)	
Min	-15	5	2
Q1	-8.3	12.5	4.3
Median	6.5	19	18.5
Q3	18	53.5	26.5
Max	21	58	37
IQR	26.3	41	22.3

Min, minimum; Q1, first quartile; Q3, third quartile; Max, maximum; IQR, interquartile range.

4.1.2. Test-Retest Reliability

The median test-retest differences in HSE for NH individuals were 12%, 4%, and 8% for NVA, BLU, and LiCoS, respectively. These values were 9%, 5%, and 5% for SQ. For the both tests, LiCoS achieved the highest $\mathrm{ICC}_{\mathrm{agreement}}$ in NH individuals (83.4% and 82.6%, see Table 4.4).

The median test-retest differences in the CI group for HSE were 8%, 16%, and 12% for NVA, BLU, and LiCoS, respectively. For SQ, they were 11%, 18%, and 10%. NVA's $\mathrm{ICC}_{\mathrm{agreement}}$ was the highest in HSE (91.7%), while LiCoS's was the highest in SQ (69.9%)(see Table 4.4).

4.1.3. Inter-Individual Variability

The interquartile range (IQR) values of the NH group in the HSE test were 37.8%, 21%, and 19.5% for NVA, BLU, and LiCoS, respectively. For SQ, the values were 26.3%, 41%, and 22.3%.

BLU had the lowest CV among NH individuals (0.20) for HSE, and LiCoS had the lowest CV for SQ (0.74) (see Table 4.4).

In summary, the results indicated that BLU and LiCoS were more optimal test materials for HSE and SQ tests compared to NVA. Although BLU and LiCoS revealed similar results in terms of effect size and inter-individual variability, LiCoS was preferred over BLU for the subsequent phases of the study due to its higher test-retest reliability especially in CI users. All the results of this phase are summarized in Table 4.4.

Table 4.4. Summary of all the results in the first phase of the study.

	Effect size (NH)	**Test-retest reliability (NH)**	**Test-retest reliability (CI)**	**Inter-individual variability (NH)**
		HSE		
NVA	43.5%	82.6%	***91.7%***	0.41
BLU	61%	81.5%	58.1%	***0.20***
LiCoS	***62%***	***83.4%***	69.1%	0.21
		SQ		
NVA	6.5%	55.3%	1.3%	3.03
BLU	***19%***	81.8%	43.8%	0.77
LiCoS	18.5%	***82.6%***	***69.9%***	***0.74***

4.2. Normative Data of HSE and SQ

Thirty NH individuals were tested to obtain normative data for the HSE and SQ tests.

An overview of the participants included in the NH group is presented in Table 4.5.

Table 4.5. Overview of the participants in the NH group.

Participant	Age	Gender	Reference ear	HSE (%)	SQ (%)
P1	28	F	L	62	23
P2	32	M	R	37	37
P3	23	F	R	55	17
P4	32	F	R	70	18
P5	36	F	L	70	12
P6	22	F	R	70	20
P7	24	M	R	23	15
P8	23	F	R	67	3
P9	23	M	L	23	18
P10	26	F	L	65	12
P11	23	M	L	35	8
P12	22	F	R	54	20
P13	26	M	L	41	10
P14	22	M	R	63	47
P15	22	M	L	57	30
P16	25	F	L	58	43
P17	24	M	R	70	37
P18	23	F	L	52	23
P19	21	F	L	70	35
P20	28	M	L	62	23
P21	30	M	R	70	28
P22	21	M	L	67	20
P23	39	F	R	60	8
P24	19	M	R	70	7
P25	33	M	R	67	27
P26	19	F	L	52	27
P27	24	F	L	67	15
P28	23	F	L	70	28
P29	21	F	R	62	3
P30	32	M	R	65	32

F, female; L, left; M, male; P, participant, R, right.

The mean HSE was 58±14% (95% confidence interval = 53 – 64%), and the mean SQ was 22±11% (95% confidence interval = 17 – 26%) in the NH group. The independent samples t-test revealed a statistically significant difference between the HSE and SQ results (p<0.01).

The initial phase of the present study revealed that the median test-retest differences in NH individuals for the HSE and SQ tests were 8% (Q1: 2 and Q3: 10) and 5% (Q1: 0 and Q3: 11), respectively.

4.3. Binaural Benefits in Bilateral CI Users

The mean HSE was 49±13% (95% confidence interval = 42 – 54%), and the mean SQ was 13±14% (95% confidence interval = 8 – 20%) in the CI group. Similar to the NH group, HSE was statistically higher than SQ (p<0.01). Furthermore, the HSE and SQ scores of the CI group were significantly lower than those of the NH group (Figure 4.3 and Figure 4.4).

While HSE was positive in all CI users in the study sample, 28% of the participants had SQ values lying under the lower cutoff of the normal zone (0.44 - 43.56%), which was derived from the data of NH.

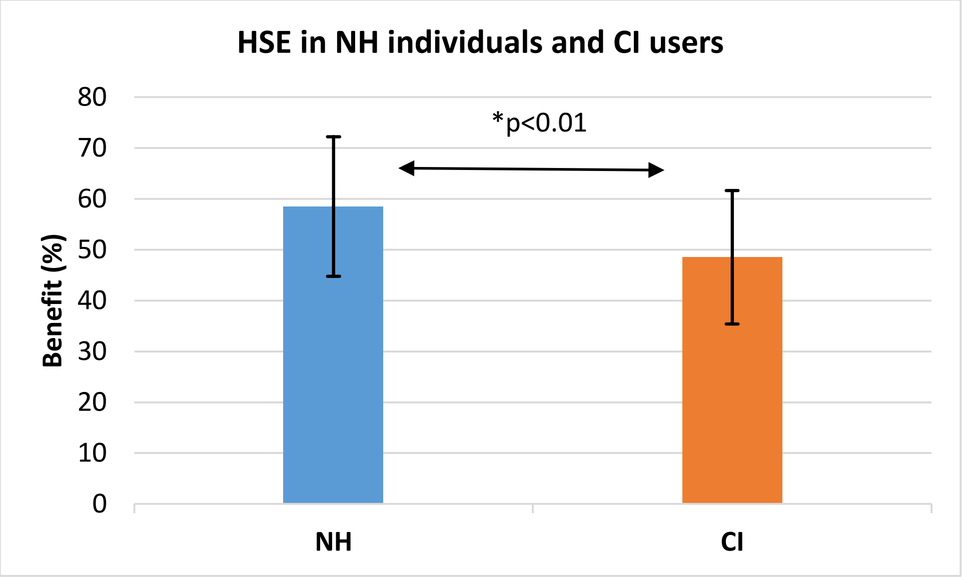

Figure 4.3. HSE results (mean±standard deviation) in NH individuals and CI users.

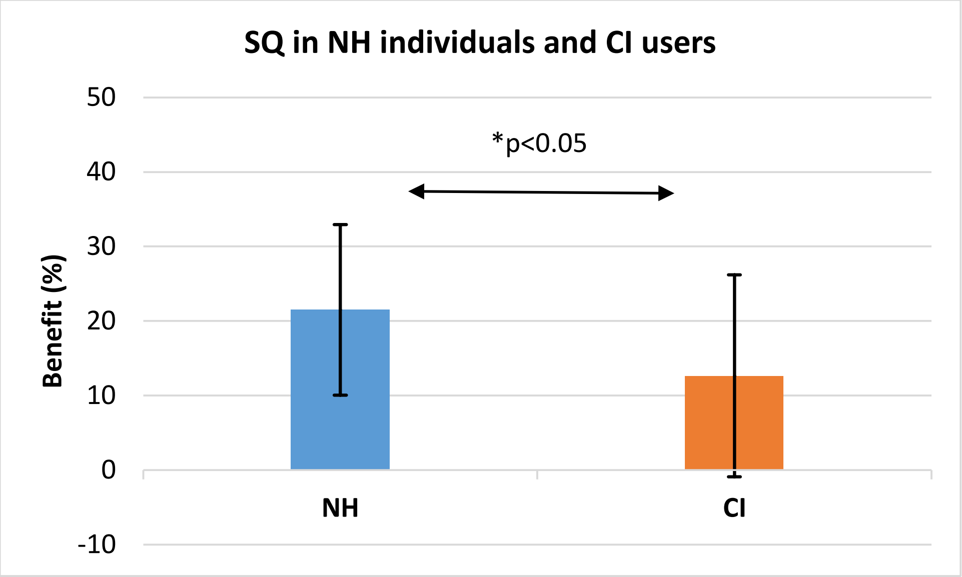

Figure 4.4. SQ results (mean±standard deviation) in NH individuals and CI users.

The average RMS error in the azimuth localization test was 15°±5 (Figure 4.5).

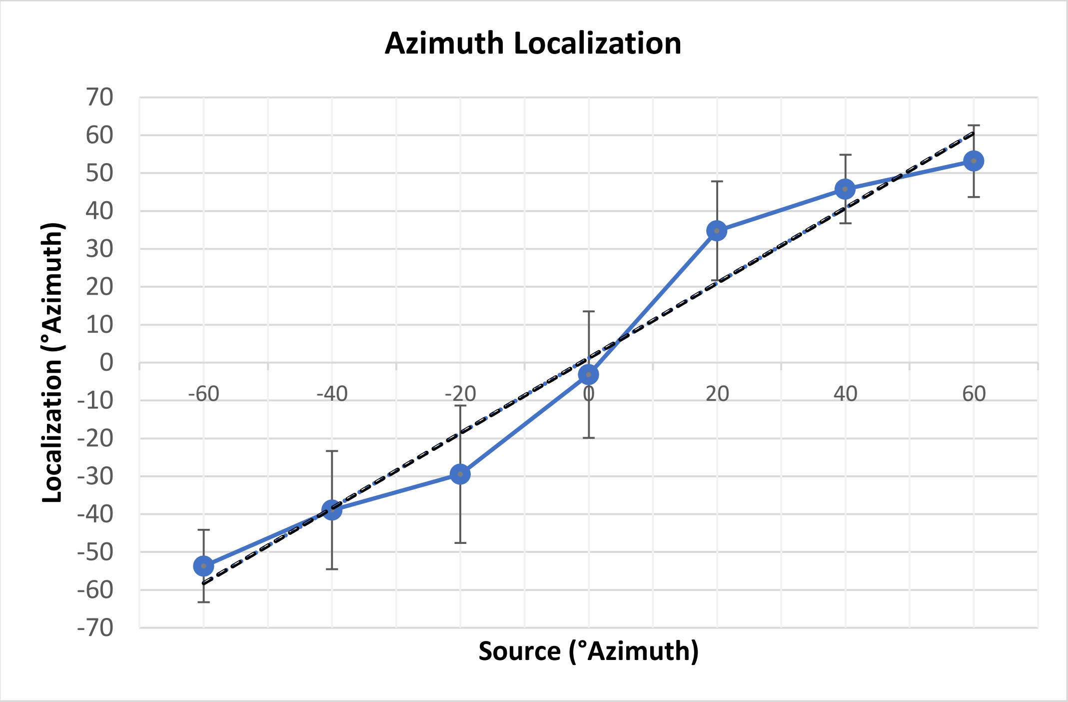

Figure 4.5. Azimuth localization test results (mean±standard deviation) (dark blue solid line) in CI users, and normal curve (black dashed line).

The average score on the SSQ was 5±2. There were no statistically significant correlations between the HSE, SQ, LOC, and SSQ results.

Further analysis did also not reveal any significant correlations between the test results and demographic variables such as age at the time of the testing, age at the 1st and the 2nd implantations, the gap between the implantations, duration of binaural experience, and asymmetry between the ears ($p>0.05$).

Although not significantly, individuals who received their first implant in the postlingual period (>4 years) performed slightly better than those implanted in the prelingual period (≤4 years). The results of the prelingual and postlingual groups were 47±13% and 52±13% for HSE, and 11±15% and 16±11% for SQ, respectively ($p>0.05$). The prelingual group had a higher SRS in their first implanted ears (87.3% vs. 82.1%) ($p>0.05$). However, there was no difference between the groups in terms of SRS of the second implanted ears (both 80.3%).

5. DISCUSSION

The primary purpose of this study was to identify which speech material is most effective for the HSE and SQ tests. Following that, normal values in NH individuals were obtained using the speech material decided to be optimal. In addition, LOC, SSQ, HSE, and SQ tests were applied to bilateral CI users with at least six months of binaural listening experience.

5.1. Optimal Speech Material for HSE and SQ

The materials tested in the initial phase included monosyllabic NVA words (127), disyllabic BLU words (127), and LiCoS sentences (128).

5.1.1. Effect Size

To the best of our knowledge, there are not other studies in the literature evaluating and comparing the effectiveness of different speech materials in HSE and SQ tests. However, when the results of a variety of studies are reviewed, it becomes apparent that the speech material influences binaural benefits. As an example, monosyllabic words have the lowest SQ effect (1.9 - 3.7 dB SRT), while disyllabic words and closed-set sentences produce similar effects (4-7 dB and 4.5-7 dB SRT, respectively) (25, 55, 56, 138). Thus, it becomes apparent that binaural benefits increase with the redundancy of the speech material of interest. In the present study, we also found that disyllabic words and sentences had the largest effect sizes both in the HSE and SQ tests. In the test setup, we create a difficult listening situation that creates gaps in the incoming acoustic signal. The test task is to fill those gaps by adding the second ear, and it turns out that this addition does so better if the acoustic material also contains redundant information.

A study conducted by Yoon et al. (139) examined the effects of contextual cues on binaural benefits using both phoneme and sentence recognition tests. When there was less than 20% asymmetry between the monaural performances of the two ears, the binaural advantages for consonants, vowels, and HINT sentences were 8.1, 8.4, and 15.6%, respectively. Also in the presence of a significant asymmetry (>20%) between the ears, the sentence stimuli provided higher scores than the phonemes, albeit not statistically. In that study, researchers assessed binaural benefit using SU. Although HSE and SQ were evaluated in the present study, and not SU, the sentence stimuli had higher scores than the monosyllabic words in which phoneme scoring was used (62% vs. 43.5% for HSE, and 18.5% vs. 6.5% for SQ). Given that each test material contains different cues, it ought not to be surprising that the results differ between materials. According to Yoon et al. (139), a possible explanation for the lower results in the monosyllabic word recognition test might be that the asymmetry in unilateral performance becomes more prominent when listening to acoustic cues rather than contextual or linguistic cues. However, only three participants in our sample had a monaural performance asymmetry above 20%. Therefore, we are not able to draw any conclusions about the effect of asymmetry on performance based on the results of the current study.

5.1.2. Test-Retest Reliability

Studies conducted so far have used a variety of speech materials. Although many researchers used sentence stimuli, some also used other materials. For example, Morera et al. (92) and Verhaert et al. (8) used disyllabic words, and Arsenault & Punch (51) used nonsense syllables. In their studies, Aronoff et al. (27) and Devocht et al. (95) evaluated test-retest variations of the materials they used, but did not compare these values with those of other materials. Aronoff et al. (27) found a statistically significant correlation between test-retest results with a correlation coefficient of 0.9. In the present study, however, the ICC method was preferred over correlation analysis since systematic differences between the test and retest data are ignored in correlation analysis. In both the HSE and SQ tests in NHs, LiCoS had an ICC value of >80%, indicating good reliability (134). For CI users, the ICC values were 69.1% and 69.9%, indicating moderate reliability. The ICC values of Dutch matrix sentences in CI users were >70% in Devocht et al. (95)’s study. While the results of the two studies are not significantly different, the methodologies do differ. Firstly, Devocht et al. (95) performed the tests on a population of 15 bimodal users. In the present study, however, each test group comprised six bilateral CI users and six NHs. In that study, ICC analysis was performed using a one-way random model, whereas in the present study, a two-way mixed model was used. With this model, the results only represent the reliability of the specific raters involved in the reliability experiment (134). The one-way random-effects model requires each participant to be rated by a different set of raters (134), which could make the method inappropriate for analyzing test-retest data from speech tests since the lists in the tests are phonetically balanced and have similar characteristics. It is also recommended by Koo & Li (134) to use the two-way mixed model in test-retest studies. When the one-way random model was used in the present study to compare the results with those of Devocht et al. (95), the ICC values of the CI users increased to ≥70%.

The median test-retest differences for NH individuals in the HSE test were 12%, 4%, and 8% for NVA, BLU, and LiCoS, respectively. In the SQ test, the differences were 9%, 5%, and 5%. The test-retest differences in NH individuals in the present study were comparable to those reported in the literature. Kim et al. (140) showed that the mean test-retest difference in monosyllabic words varied between 0.38% and 7.85%, depending on the individual's performance and the number of items in the speech list. The ICC values reported by Spyridakou et al. (141) for the right and left ears in SPIN test performed using monosyllabic words in NH individuals were 25% and 39%, respectively. The ICC values for NH individuals obtained using monosyllabic words in the present study were 82.6% and 55.3% for HSE and SQ, respectively (for LiCoS sentences the values were 83.4% and 82.6%). However, the test-retest variability observed among CI users was higher than among NH individuals. CI users had test-retest differences of 8%, 16%, and 12% in the HSE test, and 11%, 18%, and 10% in the SQ test. Studies demonstrated that test-retest variation is affected by the signal-to-noise ratio at which the test is conducted (140, 142, 143). Grange (143) showed that test-retest reliability increases as the stimulus presentation level increases. Kim et al. (140) reported that test-retest variability was 7.85% at SNRs where SRS scores varied between 46-55% and reduced to 2.73% when the scores were above 86%. Hey et al. (142) tested 38 CI users with Oldenburg sentence test. They found test-retest variations higher in CI users than in NH individuals. Researchers also revealed a positive correlation between SRTs and test-retest differences (142). In other words, test-retest differences were lower for good CI performers, while poor performers had higher test-retest differences. These results indicate that test-retest variability decreases with the increasing performance of listeners, possibly due to ceiling effect (140). The present findings also support this argument.

Even though the test-retest reliability reported in the present study is consistent with those reported in the literature, and ICC analysis shows that these tests have moderate-to-good test-retest reliability depending on the target population, the results should be interpreted with caution. Not only the HSE and SQ tests, but all tests utilizing speech audiometry possibly have this issue. As discussed above, test-retest differences in speech audiometry can reach up to 10% in NH individuals and up to 15% in CI users, making it difficult to interpret the results on an individual basis. Hence, the authors believe that interpreting the speech audiometry results, especially binaural tests' results in this case, on a group basis rather than on an individual basis will provide more reliable results.

Another important finding in the current study was that although no significant differences were observed between BLU and LiCoS in terms of interindividual variability and effect size, the test-retest reliability of LiCoS in CI users was higher than that of BLU, albeit not significantly. One could argue that the reason behind this could be differences in the number of items in each list for the given materials, as also indicated by Kim et al (140). BLU had 12 items in each list, and LiCoS had 30. However, to establish equivalence, two lists of BLU were used in the present study. As a result, a total of 24 items from BLU and 30 from LiCoS were presented to the participants. Kim et al. (140) demonstrated that there was no significant difference in test-retest reliability between 25 and 50-item lists, but there was a significant difference when a 10-item list was included in the comparison. Another possible explanation might be that BLU might have a lower inter-list equivalence compared to LiCoS (52).

5.1.3. Inter-Individual Variability

In line with previous research, the results showed considerable variation among individuals. As expected, the variability among individuals in the NH group was lower than in the CI group.

It was not surprising that the CI group's results were more variable, as a variety of factors might influence the outcomes such as the age at onset of hearing loss, the etiology, experience with acoustic hearing before implantation, individual performances of the first and the second ear, or the duration between the onset of hearing loss and implantation. Williges et al. (69) cite other possible factors increasing the variability of the results in CI users: different CI signal processing strategies, the different spread of the electrical field generated by the implant, preservation of spiral ganglion cells, and different frequency ranges of residual acoustic hearing.

5.2. Normative Data of HSE and SQ

The mean HSE was 58±14%, and the mean SQ was 22±11% in the NH group. These data are in agreement with previous research although methodological differences between the studies make direct comparisons challenging. In the literature, HSE varies between 8.9 dB – 10.7 dB in individuals with NH (25, 51), and SQ ranges between 1.9 dB – 4.9 dB (25, 51, 55-57). In test setups run at fixed SNRs, HSE ranges from 20-30% (51), and SQ between 10-26% (51, 57).

Nevertheless, there was a considerable degree of within-group variability in NHs. This finding also confirms our previous concerns regarding the high test-retest variability. Such a wide normative range makes determining whether a listener's results are normal or abnormal quite challenging. Therefore, we recommend once again comparing the results on a group basis rather than individually.

5.3. Binaural Benefits in Bilateral CI Users

Bilateral CI users in the present study had 49±13% HSE and 13±14% SQ. These results are in line with previous studies in literature in which HSE ranged from 22 to 49% and SQ from 1.7% to 18% (6-8, 12, 20, 49, 52, 111).

With regard to binaural benefits, HSE had the most robust results. In the present study, all CI users showed a positive HSE, but 72% were able to benefit from SQ. Similarly, Tyler et al. (52) and Gantz et al. (12) demonstrated that 80% of bilateral CI users had an HSE. All participants in Müller et al. (11)'s study had an HSE. A significant SQ was reported only in 3/9 participants by Tyler et al. (52) and Gantz et al. (12), but in 7/9 participants by Müller et al. (11). Litovsky et al. (4) reported that 94% of 34 simultaneously implanted bilateral CI users had HSE, while only 44% had SU and 47% had SQ. Several other studies have also reported similar findings (49, 113). Laske et al. (113) observed significant results following bilateral implantation only in HSE and no improvements in SU or SQ. Laszig et al. (49), on the other hand, found that participants in their study had HSE and SU but no significant SQ even six months following the implantation. In light of previous research and the findings of the present study, it appears that a less number of CI users can benefit from SQ. As a matter of fact, most of the benefits of bilateral implantation can be attributed to HSE. The reason why HSE is so advantageous is that it ensures in any case that at least one ear has a favorable SNR.

Overall, the results of CI users were significantly lower than those of NH individuals. Other studies also reported similar results (25, 51, 110). One might assume that the wider age range in the CI group may have led to lower results in the present study. However, there were only five participants above the upper age limit of the NH group. Furthermore, the results of those five participants were not different than the rest of the group. A functional hearing system is able to process and integrate bilateral acoustic cues smoothly. However, it is not always possible to achieve a similar success in artificial hearing provided by electrical stimulation in CI users. CI users perform less well in binaural hearing tasks than NH people for a variety of reasons. Most notably, CI users have a reduced ITD and ILD sensitivity in addition to inadequately encoded TFS information with current sound processing strategies (4, 46, 48, 110). In their study, Litovsky et al. (144) outlined three main reasons for reduced binaural advantages in CI users: "hardware- and software-related, surgical-based, and pathology-related". In summary, CI users have two independent monaural hearing systems. Thus, the time base of each processor can differ slightly, resulting in random jitters in the ITD of the envelope and the carrier pulses, disrupting the ITD cues (144). Most CI systems process incoming signals by extracting only the temporal envelope and amplitude-modulating it to a fixed-rate pulsatile carrier (74). They do not provide the TFS information that is critically important for detecting ITDs (145). Despite the potential for the temporal envelope to convey timing information, ITDs would not be consistent because of the variations in detection thresholds across different electrodes

(74). Furthermore, although CI users' speech understanding improves with higher pulse rates, their ITD sensitivities drop significantly (146-148). Additional factors that may distort binaural cues include different microphone characteristics, independent automatic gain control and compression algorithms, and different signal processing strategies between the two implants (46, 48, 52, 74, 108, 144, 149). For instance, when one of the processors compresses its input more than the other, the brain perceives the sound as moving from one side to the other, which may negatively affect spatial hearing (48). Another problem is the spectral mismatch between the electrodes due to the different surgical insertion depths. Accordingly, Yoon et al. (150) found that increased spectral mismatch caused by different insertion depths affected SQ negatively, but not HSE. A binaural cochlear implant may eliminate the aforementioned problems of two independent cochlear implant systems. A binaural cochlear implant has two different electrode arrays protruding from a single internal device, and these electrodes are placed in both cochleae. While there is a sound processor on the side of the internal device, the contralateral ear only has a microphone connected to the sound processor by a cable. Verhaert et al. (8) investigated the effects of binaural cochlear implantation after 12 months of use in 14 adults with postlingual hearing loss. There was a significant difference between participants' SRSs in silence and noise in the binaural condition compared with the unilateral condition. Significant binaural advantages were present in HSE, SU, and SQ tests. In addition, a significant improvement of 35° RMS was observed in localization task. These results confirm that pseudosynchronous stimulation of binaural cochlear implants has positive effects on binaural hearing and that unsatisfactory results in bilateral CI users may be due to a mismatch in two independent implant systems.

There was no significant correlation between HSE/SQ test results and LOC. Similarly, Schleich et al. (5) and Tyler et al. (108) also could not find a significant correlation between HSE/SQ and horizontal LOC in bilateral CI users. While HSE is not directly related to spatial listening, it is believed that SQ relies on the same binaural cues that allow the localization of sound sources (7). It was therefore expected that LOC and SQ results would have a correlation. Assuming that these two phenomena use the same interaural cues, it is odd that there was no significant correlation between them. This raises the question of whether they represent the ability to use the same cues. Cox & Bisset (151) put forward a similar idea. In their study, researchers presented binaural and pseudobinaural stimuli to HA users. The participants had to select the stimulus that was more clear/intelligible. Selecting the binaural stimulus as more intelligible indicated the presence of SQ since binaural stimuli contained both ITD and ILD cues as opposed to pseudobinaurals. Participants who demonstrated SQ using traditional testing methods were unable to differentiate between binaural and pseudobinaural stimuli. Researchers concluded that SQ tested with traditional methods does not reflect the ability to exploit interaural differences.

The SSQ was used in the present study to examine how well the laboratory results matched patients' daily life experiences. However, SSQ scores were not significantly correlated with HSE/SQ or LOC results. Using a similar sample of 34 bilateral CI users with at least six months of binaural experience, Laske et al. (113) found that the LOC results were significantly correlated with the "spatial hearing" subcategory of the SSQ. Despite similar patient populations, there were several methodological differences between the two studies, including the type of noise (broadband vs. speech), the total number of speakers (12 vs. 7), and the number of items in the SSQ (25-item vs. 12-item). These methodological differences may have led to different results in the studies.

There were no statistically significant correlations between HSE-SQ results and age, age at the 1st and 2nd implantations, the gap between the implantations, duration of binaural experience, or asymmetry between ears. Additionally, correlation analyses were performed separately for individuals implanted in the prelingual and postlingual periods. However, there was still no significant correlation between the variables and the HSE, SQ, and LOC test results. Although not significantly, individuals who received their first implant in the postlingual period performed slightly better than those implanted in the prelingual period. The duration of exposure to an acoustic hearing before implantation might explain the difference in binaural hearing abilities between the two groups. Following implantation in adults in the postlingual period, hearing systems previously exposed to acoustic stimuli will be reactivated by electric stimulation, and the already developed binaural pathways will be maintained (144). Children with CI, however, have little or no experience with acoustic hearing before the implantation since they usually lose their hearing at birth or during the first few years of life. Consequently, their hearing systems develop very differently from adult CI users (144). It is noteworthy that some study participants implanted during the prelingual period showed progressive hearing loss. This finding suggests that these participants in the prelingual group may have been exposed to some acoustic hearing during the pre-implantation period and may have accordingly enhanced binaural hearing abilities. Perhaps this explains the absence of statistical significance between the groups implanted prelingually and postlingually. Thakkar et al. (125) also showed that exposure to acoustic hearing at an early age increases sensitivity to ITD cues and binaural hearing advantages. Perhaps for this reason, at least for binaural hearing assessments, it would be more relevant to define the groups based on the exposure to the acoustic hearing before the implantation instead of the age at the implantation (prelingually or postlingually implanted).

The results of the present study showed that none of the variables investigated correlated with the binaural hearing advantages. Similarly, Schleich et al. (5), Tyler et al. (108), and Laske et al. (113) could not find a relationship between binaural benefits and other variables. These findings support the argument of Gantz et al. (12) that there is no parameter for predicting the postoperative binaural benefits. We believe that the main reason for this result is the high variation in both individual and group results observed in the HSE and SQ tests.

5.4. Other Factors Influencing the Results

There are many factors that influence the results of binaural tests. These factors include different test setups (fixed SNR or adaptive algorithm), noise types, reference ears (the first implanted ear or the best ear) as well as the number and position of speakers (11, 13, 49, 63, 152, 153). It is, in fact, impossible to accurately represent real-life situations in a lab environment. Signal and noise sources are not stationary in real life, and their locations can change frequently. In addition, even though HSE and SQ benefits are tested separately, these effects interact and occur simultaneously in real life (4, 96).

There are two ways to conduct HSE and SQ tests in NH people. The first method utilizes the Knowles Electronic Manikin for Acoustic Research (KEMAR), which resembles the head and upper body structures of a human (154) and can create ITD and ILD cues. This method involves placing a microphone on or near the eardrum of the manikin, making recordings in the free field, and then presenting the recordings over headphones to the listeners (25, 51, 64). Alternatively, the tests can be conducted directly in the free field by blocking and masking one ear during monaural listening situation (55-57). However, this method may cause problems in eliminating the contribution of the second ear during monaural listening. Furthermore, the non-reference ear is given additional noise, whose effect on the central hearing system is uncertain. KEMAR, however, offers the ease in eliminating the second ear in the monaural listening condition. A disadvantage of using KEMAR is that a single HRTF recording might not be representative enough, as each individual's head, body, and ear structures are different (29, 155-157).

HSE and SQ tests can be conducted at a fixed SNR or using an adaptive test algorithm. Signal and noise intensities are constant at fixed SNRs, and the score is derived by calculating the percentage of correctly repeated items. Adaptive algorithms, on the other hand, vary the intensity of either noise or signal and determine the SNR at which a predefined percentage of correctly repeated answers is obtained. From a theoretical perspective, fixed- and adaptive testing paradigms differ in their methodology. As a result of utilizing percent-correct scores that are not normally distributed around the mean, the fixed paradigm results in a non-linear performance-intensity function, where obtaining significant differences between conditions is more difficult at mid-range scores than at lower or higher scores (96). Second, there is a likelihood that around 50% of participants will not show a significant difference between conditions in the fixed paradigm due to ceiling and floor effects (5, 49, 96). The third caveat is that the fixed paradigm requires only a single measurement per condition (158), while adaptive procedures yield an SRT based on repeated measurements for the same condition (96).

According to Schafer et al. (96), the fixed- paradigm provides a statistically better measure of true SQ performance than the adaptive paradigm. Compared to the adaptive method, the fixed-testing paradigm yielded slightly larger effect sizes for all three binaural phenomena (HSE, SQ, and SU) (96). According to the researchers, the larger effect sizes at fixed SNRs resulted from the fact that the tests were conducted at suprathreshold levels (96). A disadvantage of the adaptive algorithm is that poor performers may have difficulties completing the SPIN tests at SNRs close to the threshold levels (95, 96, 159). This may result in a higher SRT than the actual SRT (95, 160) and high test-retest differences (159), decreasing the reliability of the results. According to Kaandorp et al. (159), SRTs higher than 15 dB SNR obtained by an adaptive paradigm should be considered unreliable. Several other studies included individuals only with SRSs greater than 50% to overcome this issue (95, 161, 162). Additionally, some studies also used a wide range of fixed SNRs (139). The present study used both fixed- and adaptive algorithms. An adaptive algorithm was used to obtain an SRT threshold of 70% correct responses in the binaural listening condition. Then, the test in the monaural condition was conducted at that SRT level. To the best of our knowledge, no other study employed such a test method in the literature, making it difficult to compare the present results with those from other studies. Contrary to many studies in the literature, the target percentage of correctly repeated answers in the adaptive algorithm was 70% in the present study. The reasons for this were 1) to remain above the threshold, 2) to have more room downwards for lower test results in the monaural situation, and 3) to avoid ceiling effects in people with NH, and CI users with high SRS. Even with one ear/CI, these individuals achieve such low SRTs that the second ear/CI adds nearly no benefit. To overcome this problem, Vermeire & Van de Heyning (114) propose two approaches as we also employed in the present study: 1) using more difficult speech materials and 2) using an adaptive procedure with a higher target of correct answers (75 or 80%).

Another important factor that may affect the results is the reference ear in the monaural condition. The present study used the first implanted ear as the reference ear. Clinical practice was the underlying reason for this preference. The primary purpose of the binaural assessment is to determine what the second implant will add to a unilateral CI user. Thus, choosing the first implanted ear as the reference ear will provide more realistic and achievable results in clinical practice. In addition, the first implanted ear contributes more to spatial hearing than the second (119). Van Hoesel

& Litovsky (47) reported that choosing a fixed ear as the reference ear (for example, the first implanted ear) may overestimate the binaural benefits if the second implanted ear performs better than the first. However, in the present study, the first implanted ears had statistically better audiometry and speech audiometry results than the second implanted ears. The underlying reason may be that the first CIs were exposed to auditory stimuli longer than the second CIs, resulting in a better-developed neural reorganization (121). One may also assume that there might be an underestimation of binaural benefits due to statistical sampling bias that favors the monaural condition if the reference ear is the one that performs better. However, van Hoesel & Litovsky (47) reported in their study that the statistical bias that occurs when the reference ear is the better-performing ear varies between 0.1 dB and 0.7 dB depending on the test-retest reliability of the speech material of interest.

To the best of our knowledge, the present study is the first in the literature investigating the effect of speech material on HSE and SQ assessments. In this sense, it is an original piece of work. With the optimal speech material selected, normative data were obtained in NH individuals, and the results are expected to serve as a reference for future studies in the literature that will use the same speech material. The present study also evaluated the relationship between binaural hearing outcomes and other variables in CI users. A limitation of the present study was the heterogeneity of the CI group. Including only prelingually or postlingually implanted individuals within a narrower age range can increase group homogeneity and allow more accurate comparisons in future studies. Future studies should also employ larger patient populations to overcome high within-subject and within-group variability.

6. CONCLUSIONS

The primary purpose of this study was to identify which speech material is most effective for the HSE and SQ tests. The results showed that although there were no significant differences between disyllabic words and sentences in terms of effect size and inter-individual variability, test-retest reliability was higher with sentence stimuli, especially in CI users.

HSE was present in all CI users participating in the study, while 72% had SQ. In conclusion, it is evident that bilateral CI users benefit from their second implant. HSE plays a major role in this process in all participants, and SQ contributes to seven out of ten of the cases.

The LOC and SSQ test results were not correlated with the HSE or SQ results. Additionally, there was no significant correlation between the results and any other variables. The HSE and SQ results of postlingually implanted participants were slightly higher than those implanted prelingually, although not statistically.

Even though the test-retest reliability reported in this study is consistent with those reported in the literature, the results should be interpreted with caution. Considerable test-retest variations in both HSE and SQ tests make it challenging to interpret the results on an individual basis. Hence, the authors believe that interpreting the speech audiometry results, especially binaural tests’ results in this case, on a group basis rather than on an individual basis will provide more reliable results.

A limitation of this study was the heterogeneous nature of the CI group. Future research in this area should explore how these results relate to ITD and ILD cues. In addition, revealing the factors that affect binaural hearing by using larger and homogeneous patient populations to overcome high test-retest and within-group variations will shed light on future research and clinical applications.

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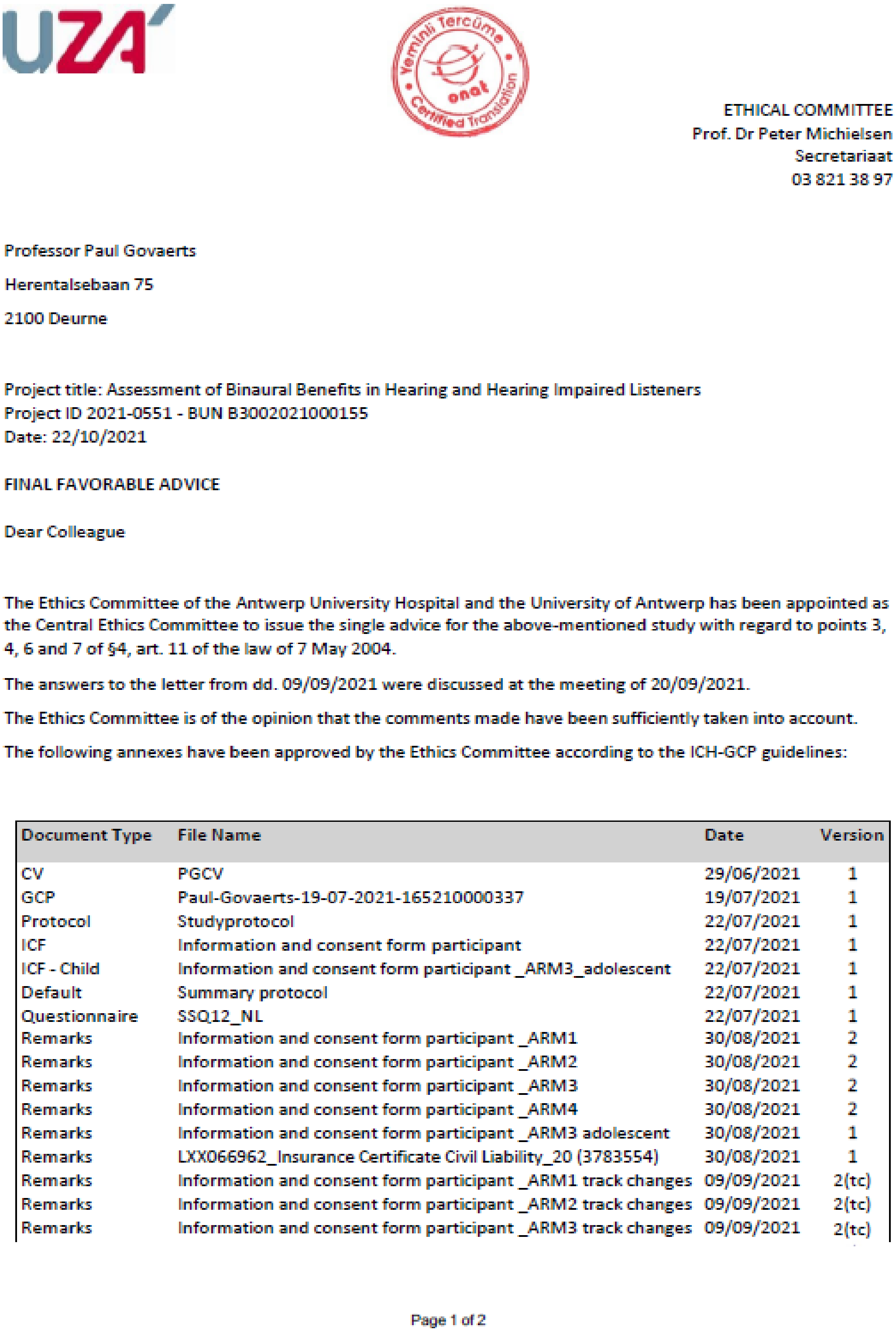
8. APPENDICES

8.1. APPENDIX-1: Ethical Approval



Yeminli Tercüme onat Certified Translation

ETHICAL COMMITTEE
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Project title: Assessment of Binaural Benefits in Hearing and Hearing Impaired Listeners
Project ID 2021-0551 - BUN B3002021000155
Date: 22/10/2021

FINAL FAVORABLE ADVICE

Dear Colleague

The Ethics Committee of the Antwerp University Hospital and the University of Antwerp has been appointed as the Central Ethics Committee to issue the single advice for the above-mentioned study with regard to points 3, 4, 6 and 7 of §4, art. 11 of the law of 7 May 2004.

The answers to the letter from dd. 09/09/2021 were discussed at the meeting of 20/09/2021.

The Ethics Committee is of the opinion that the comments made have been sufficiently taken into account.

The following annexes have been approved by the Ethics Committee according to the ICH-GCP guidelines:

Document Type	File Name	Date	Version
CV	PGCV	29/06/2021	1
GCP	Paul-Govaerts-19-07-2021-165210000337	19/07/2021	1
Protocol	Studyprotocol	22/07/2021	1
ICF	Information and consent form participant	22/07/2021	1
ICF - Child	Information and consent form participant _ARM3_adolescent	22/07/2021	1
Default	Summary protocol	22/07/2021	1
Questionnaire	SSQ12_NL	22/07/2021	1
Remarks	Information and consent form participant _ARM1	30/08/2021	2
Remarks	Information and consent form participant _ARM2	30/08/2021	2
Remarks	Information and consent form participant _ARM3	30/08/2021	2
Remarks	Information and consent form participant _ARM4	30/08/2021	2
Remarks	Information and consent form participant _ARM3 adolescent	30/08/2021	1
Remarks	LXX066962_Insurance Certificate Civil Liability_20 (3783554)	30/08/2021	1
Remarks	Information and consent form participant _ARM1 track changes	09/09/2021	2(tc)
Remarks	Information and consent form participant _ARM2 track changes	09/09/2021	2(tc)
Remarks	Information and consent form participant _ARM3 track changes	09/09/2021	2(tc)

Remarks	Information and consent form participant _ARM3 track changes	09/09/2021	1(tc)
Remarks	Information and consent form participant _ARM4 track changes	09/09/2021	2(tc)

The following comment was made:

1. According to our lawyers, no test subjects insurance is provided in the insurance certificate. Please provide this to us.

This approval is valid until one year after the above date. Please inform us when the first participant was included, when and why the study was stopped (early) or never started.

If the study is still ongoing after one year, we expect a follow-up report in which any incidents are reported.

Finally, we would like to point out that, for studies ongoing at the UZA, serious adverse events must be reported via the incident reporting system.

Kind regards

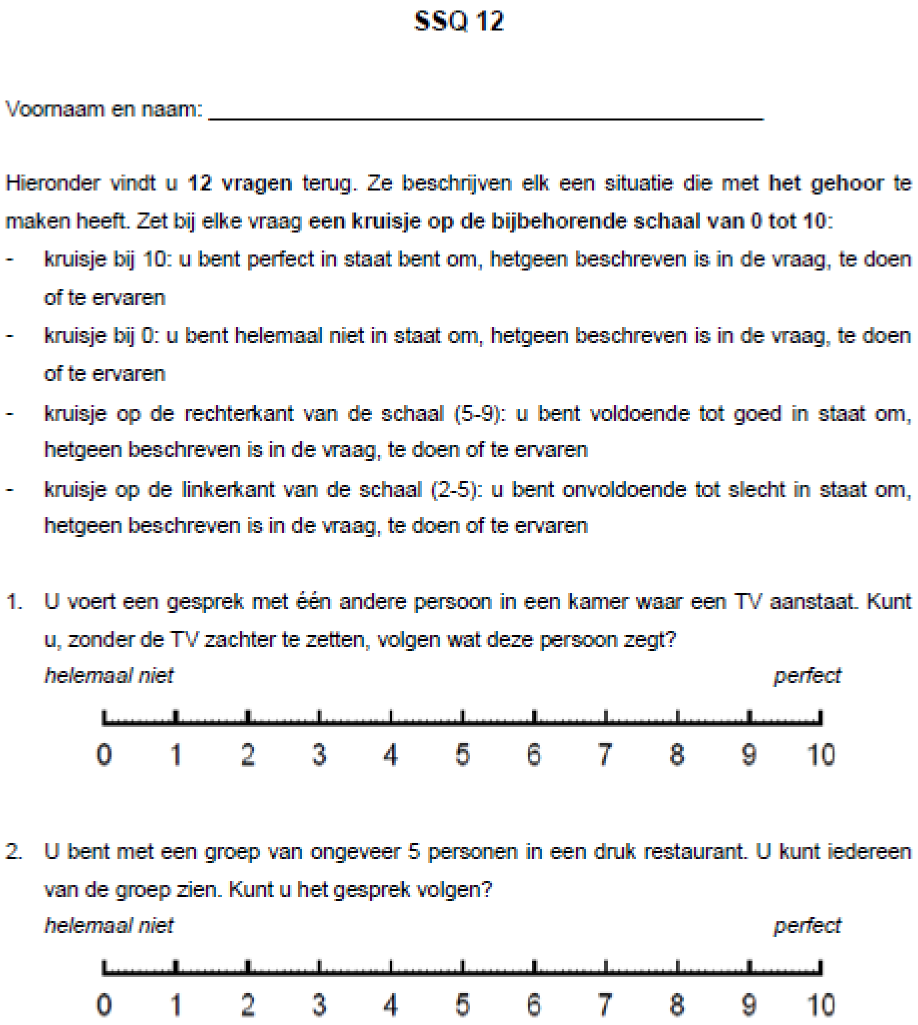
[signature]
Prof. dr. Peter Michielsen
Voorzitter Ethisch Comité UZA/UAntwerpen

cc. FAGG - Research & development departement, Victor Hortaplein 40 b40 - 1060 Brussel

Meeting Attendee Full Name	Meeting Attendee Qualifications
Ms Bettina Blaumeiser	Physicians
Emeritus Professor Hilde Bortier	MD, PhD
Prof. Dr. Patrick Cras	Vice-Chair, Physicians
Ms Ingrid De Meester	Pharmacologist
Ms Elyne Debaetselier	Nurse
Prof. Dr. Greet Ieven	Vice-Chair, Physician
Ms Johanna Kwakkel-van Erp	Physicians
Mr Peter Michielsen	Chair, Physicians
Mr Pieter Moons	Coordinator Bio- and Human Tissue bank
Ms Veerle Schoeters	Nurse
Mr Filip Van den Eede	Physicians
Mr Pieter Van Dyck	Physicians
Mr Guy Van Honste	Patient Representative
Mr Joris Verlooy	Physicians

This document is translated from Dutch to English by certified translator Betül BEKTAŞ on 27.07.2022

8.2. APPENDIX-2: 12-item version of the SSQ



SSQ 12

Voornaam en naam: ______________________________

Hieronder vindt u **12 vragen** terug. Ze beschrijven elk een situatie die met **het gehoor** te maken heeft. Zet bij elke vraag **een kruisje op de bijbehorende schaal van 0 tot 10**:

- kruisje bij 10: u bent perfect in staat bent om, hetgeen beschreven is in de vraag, te doen of te ervaren
- kruisje bij 0: u bent helemaal niet in staat om, hetgeen beschreven is in de vraag, te doen of te ervaren
- kruisje op de rechterkant van de schaal (5-9): u bent voldoende tot goed in staat om, hetgeen beschreven is in de vraag, te doen of te ervaren
- kruisje op de linkerkant van de schaal (2-5): u bent onvoldoende tot slecht in staat om, hetgeen beschreven is in de vraag, te doen of te ervaren

1. U voert een gesprek met één andere persoon in een kamer waar een TV aanstaat. Kunt u, zonder de TV zachter te zetten, volgen wat deze persoon zegt?

   helemaal niet *perfect*

   0 1 2 3 4 5 6 7 8 9 10

2. U bent met een groep van ongeveer 5 personen in een druk restaurant. U kunt iedereen van de groep zien. Kunt u het gesprek volgen?

   helemaal niet *perfect*

   0 1 2 3 4 5 6 7 8 9 10

3. Terwijl u luistert naar iemand die tegen u praat, probeert u ook het nieuws op de TV te volgen. Kunt u volgen wat beide sprekers zeggen?

helemaal niet *perfect*

0 1 2 3 4 5 6 7 8 9 10

4. U voert een gesprek met één persoon in een ruimte waarin meerdere personen praten. Kunt u volgen wat de persoon met wie u het gesprek voert, zegt?

helemaal niet *perfect*

0 1 2 3 4 5 6 7 8 9 10

5. U voert een gesprek in groep waarbij de sprekers voortdurende wisselen. Kunt u het gesprek gemakkelijk volgen, zonder de eerste woorden van iedere nieuwe spreker te missen?

helemaal niet *perfect*

0 1 2 3 4 5 6 7 8 9 10

6. U bent buiten. Een hond blaft luid. Kunt u onmiddellijk zeggen waar de hond zich bevindt, zonder te kijken?

helemaal niet *perfect*

0 1 2 3 4 5 6 7 8 9 10

7. Kunt u, op basis van het geluid afleiden hoe ver een bus of vrachtwagen van u verwijderd is?

helemaal niet *perfect*

0 1 2 3 4 5 6 7 8 9 10

8. Kunt u, op basis van het geluid, zeggen of een bus of vrachtwagen naar u toe rijdt of van u wegrijdt?

helemaal niet *perfect*

0 1 2 3 4 5 6 7 8 9 10

9. Wanneer u meer dan één geluid tegelijkertijd hoort, heeft u dan de indruk dat u een mengelmoes van geluiden hoort?

Een mengelmoes *Afzonderlijke geluiden*

0 1 2 3 4 5 6 7 8 9 10

10. Wanneer u muziek beluistert, kunt u dan bepalen welke instrumenten worden bespeeld?

Helemaal niet *perfect*

0 1 2 3 4 5 6 7 8 9 10

11. Klinken alledaagse geluiden, die u goed hoort, helder (niet vaak of wazig)?

Helemaal niet *perfect*

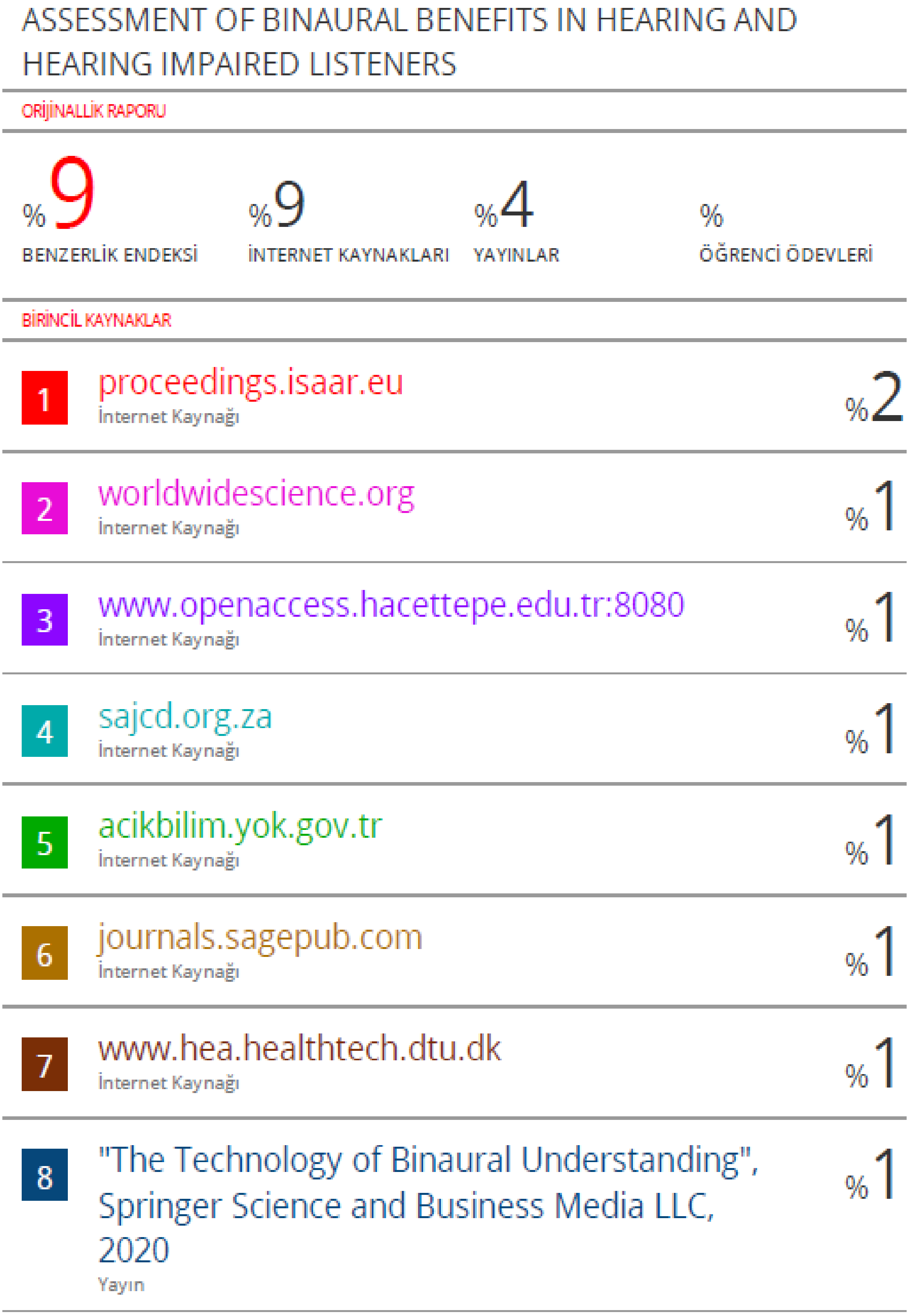
0 1 2 3 4 5 6 7 8 9 10

12. Moet u zich erg concentreren wanneer u naar iets of iemand luistert?

erg concentreren *geen concentratie nodig*

0 1 2 3 4 5 6 7 8 9 10

8.3. APPENDIX-3: Turnitin Originality Report



ASSESSMENT OF BINAURAL BENEFITS IN HEARING AND HEARING IMPAIRED LISTENERS

ORİJİNALLİK RAPORU

%9	%9	%4	%
BENZERLİK ENDEKSİ	İNTERNET KAYNAKLARI	YAYINLAR	ÖĞRENCİ ÖDEVLERİ

BİRİNCİL KAYNAKLAR

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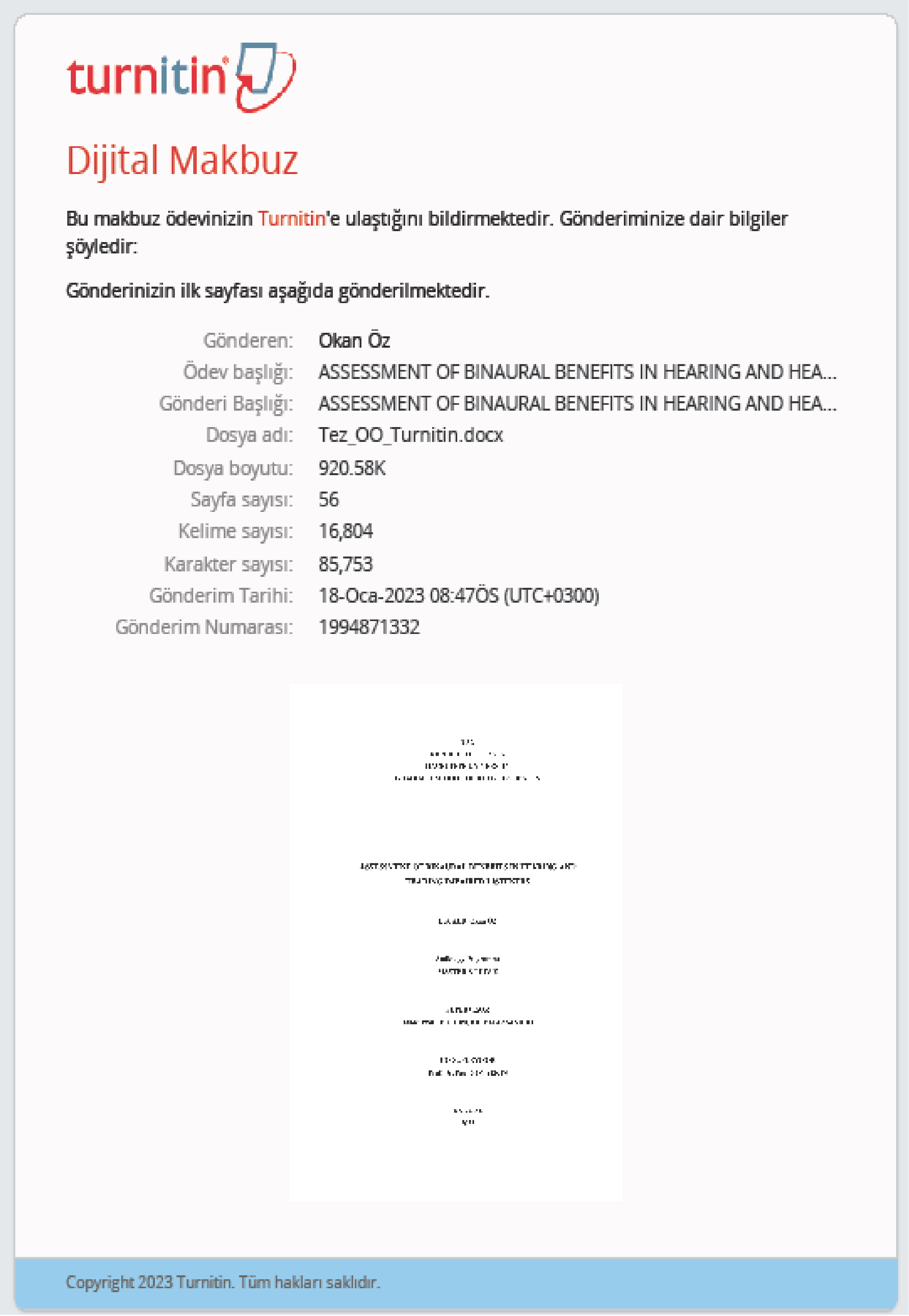
8	"The Technology of Binaural Understanding", Springer Science and Business Media LLC, 2020 Yayın	%1

8.4. APPENDIX-4: Turnitin Digital Receipt



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9. CURRICULUM VITAE (CV)

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Current position:

Correspondence address:

Gsm:

E-mail:

2. Education

3. Work Experience

4. Fields of Interest

5. Publications & Co-authorships