The Relationship Between Extended High-Frequency Hearing, Speech-in-Noise Perception, and Auditory Working Memory: A Normative Study

A Senior Thesis

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By

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Abstract

The most difficult communication environment (e.g., listening and remembering what was said) for adults is listening to speech in background noise. This poses the question of what factors can explain the reason for difficulties hearing speech-in-noise. Extended high-frequency (EHF) thresholds assess hearing in a higher frequency range than standard audiometric testing and can be used to assess cochlear health. It was hypothesized that poorer thresholds in the EHF range would be correlated with poorer speech-in-noise performance in comparison to other normal-hearing peers. Previous publications have shown that speech-in-noise performance is strongly correlated with working memory. This study also aimed to explore the interplay between auditory working memory and speech-in-noise performance and hypothesized that poorer auditory working memory capacity would be correlated with poorer speech-in-noise performance in comparison to other normal-hearing peers. In full, this study hypothesized that variation in speech-in-noise performance of normal hearers would be driven by EHF thresholds and auditory working memory capacity, such that those with poorer speech-in-noise performance would have poorer EHF thresholds and auditory working memory capacity, although within normal limits. Sixteen young adults with normal standard audiometric thresholds participated in this study. Results showed a significant positive relationship between EHF thresholds and speech-in-noise performance, confirming that poorer EHF thresholds were associated with poorer speech-in-noise performance. Trends were also seen amongst speech-in-noise performance and auditory working memory, suggesting that poorer auditory working memory capacity was associated with poorer speech-in-noise performance. Results from this study were true to the original hypotheses – poorer speech-in-noise performance in normal hearing adults was associated with poorer EHF thresholds and poorer auditory working memory capacity.

Acknowledgements

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Chapter 1

Introduction and Literature Review

The most difficult listening environment is understanding speech in the presence of background noise, or speech-in-noise. It was estimated that 12-29% of the world's population struggles hearing speech-in-noise daily despite having clinically normal thresholds (Tremblay et al., 2015; Garstecki, 1987). These individuals were referred to as having 'hearing difficulties' (HD). There are many proposed contributors to HD such as elevated extended high-frequency thresholds (Badri et al., 2011; Yeend et al., 2019), deficits in auditory processing such as poorer than normal frequency resolution (Badri et al., 2011), or cognitive deficits (i.e., deficits in attention or working memory; Yeend et al., 2019), yet there is no definitive cause. Yeend et al. (2019) explored several factors that were believed to be possible causes of speech-in-noise difficulties. Out of all possible contributors, they found that extended high-frequency thresholds and working memory were the main factors that could be significant predictors of speech-in-noise performance. However, Yeend et al. (2019) measured working memory with a reading task, evaluating the visual modality of working memory, but this relationship has yet to be evaluated with the inclusion of an *auditory* working memory task. The purpose of the current study was to evaluate the relationship between speech-in-noise performance, extended high-frequency hearing, and auditory working memory in a normative sample.

Speech-in-Noise Performance:

Audiograms allow audiologists to map a listener's pure-tone thresholds in quiet, however, there is no way for an audiogram to predict how well a patient can hear speech-in-noise (Killion & Niquette, 2000). Many patients with HD will receive hearing tests at an audiology clinic only for the clinician to inform them that they have a normal audiogram, but we know that

this cannot accurately predict speech-in-noise performance. Leaving the audiologist's office with no answers causes patients to withdraw from social situations, pretend to understand what was said, or guess in social situations, which leads to a significantly lowered quality of life for these individuals (Hallberg et al., 2008). In addition to social withdrawal, there is also increased prevalence of anxiety and depression among those with HD (Jones et al., 1984; Tremblay et al., 2015; Saunders & Haggard, 1989; Spankovich et al., 2018). Being left with no answers can also enhance the stigma related to hearing problems, as having no answers as to why they are experiencing difficulties encourages those struggling to deny, minimize, or avoid talking about their hearing problems (Hetu et al., 1990).

With or without hearing loss, almost everyone understands speech better in a quiet environment. Every individual struggles hearing speech in noise to a certain extent, even with normal hearing and no expressed complaints about speech-in-noise perception. Even in the normal-hearing population, there is considerable variation among speech-in-noise performance (Surprenant & Watson, 2001). There are many factors beyond the auditory system that are believed to affect this, such as decoding skills, attention, language skills, and working memory (Beck et al., 2018). Of all factors, the present study hypothesized that extended high-frequency thresholds and auditory working memory would be significant factors explaining the variability of speech-in-noise performance in a normative sample.

Extended High-Frequency Hearing:

Extended high-frequency (EHF) hearing refers to thresholds between 9,000 and 20,000 Hz. Most of the energy in speech is in the region from 250 to 8,000 Hz, but human hearing extends up to 20,000 Hz, a region that is rarely evaluated in standard audiologic testing. This region of hearing can reveal a lot of information about cochlear health, as EHF sounds are coded

at the base of the cochlea, which is typically the first region to experience damage due to exposure to excessive noise or ototoxic drugs/inhalants (Valiente et al., 2014). It has been shown that individuals with noise exposure are more likely to have increased thresholds in the EHF region than any other region of hearing, as compared to age-matched peers with no noise exposure (Borchgrevink et al., 1996; Liberman et al., 2016). Because this region of hearing can reveal so much about cochlear health, it is believed that thresholds in this region are a predictor of how well speech is perceived in various environments, such as noise (Zadeh et al., 2019).

Liberman et al. (2016) compared EHF thresholds and speech-in-noise performance in two groups of participants – with and without high levels of noise exposure. They found that the group with noise exposure had poorer thresholds in the EHF region and poorer speech-in-noise performance compared to the group without noise exposure (Liberman et al., 2016). Studies have shown that elevated thresholds in the EHF region are significantly correlated with a reduced ability to perceive speech-in-noise (Badri et al., 2011; Yeend et al., 2019). It has also been shown that EHF information in speech is very useful in understanding speech sounds, especially when low- and mid-frequency information is degraded or absent (Lippmann, 1996; Vitela et al., 2015). Yeend et al. (2019) suggested that EHF thresholds be tested clinically among individuals struggling with HD as a diagnostic basis for these difficulties. While EHF thresholds are often excluded from clinical testing, they are crucial for speech understanding in noise, where speech signals are often degraded (Hunter et al., 2020).

There have been multiple studies confirming a relationship between hearing thresholds and working memory capacity, suggesting that a greater degree of hearing loss is associated with poorer working memory and executive cognitive function, especially evident in older adults (Harrison Bush et al., 2015; Lin et al., 2011). However, few studies have explored the

relationship between working memory and EHF thresholds. One study suggests that poorer EHF thresholds are related to poorer cognitive abilities, with a highlight on executive functioning (Brännström et al., 2018). Executive functioning encompasses working memory, so it is likely that higher EHF thresholds are also associated with poorer working memory function, but this link has yet to be directly studied (Brännström et al., 2018).

Thresholds in the EHF region can reveal a lot about cochlear health and speech-in-noise abilities. Poorer thresholds in the EHF region predict both poorer cochlear health and a poorer ability to understand speech, especially in the presence of background noise. Further insight in this area may allow audiologists to see speech-in-noise difficulties or elevated EHF thresholds as warning signs and allow audiologists to make recommendations on hearing preservation before further cochlear damage occurs.

Auditory Working Memory:

Cognitive working memory is required for all conversational speech, as the listener must remember each piece of speech before processing. According to Yeend et al. (2019), cognitive working memory is a significant predictor of speech-in-noise performance, such that poorer working memory is correlated with poorer speech-in-noise performance. However, this finding has yet to be extended to *auditory* working memory. Yeend et al. (2019) used the Reading Span Test (Daneman & Carpenter, 1980) to evaluate the visual modality of working memory, whereas the present study used the Word Auditory Recognition and Recall Measure (Smith et al., 2016), an auditory adaptation of the Reading Span Test, to evaluate the auditory modality of working memory and its impact on speech-in-noise performance. It is already known that auditory working memory, while a cognitive process, drives our biological response to sound (i.e., ability

to hear and process speech), so it is likely that it is also a driving force behind the ability to understand speech-in-noise (Kraus et al., 2012). Kraus et al. (2012) also suggested that better auditory working memory and attention capacities are associated with enhanced cortical plasticity, which allows the auditory cortex to become more primed to process incoming speech signals.

Results from research on the relationship between working memory and speech-in-noise performance have been mixed. One study has suggested that working memory and speech-in-noise performance are largely independent of one another in young listeners with normal hearing (Füllgrabe & Rosen, 2016). Another study by Schoof and Rosen (2014) suggests that age-related declines in cognitive processes such as working memory are not indicative of speech-in-noise deficits. However, other studies have argued just the opposite. One study argued that, when it comes to individuals with hearing loss, those with a greater working memory capacity have significantly better performance understanding speech-in-noise (Rudner et al., 2011). Yeend et al. (2019) also argued that working memory is one of the few significant predictors of speech-in-noise performance. Across all four of these studies, working memory was measured using a reading span task, measuring visual and cognitive modalities of working memory, but there was no inclusion of an auditory working memory task.

Another study composed by Gordon-Salant and Cole (2016) included two types of working memory tasks – a reading span and a listening span task – to assess working memory in both visual and auditory modalities. They compared two groups, younger listeners and older listeners, both with normal hearing, to draw comparisons among age, working memory capacity, and speech-in-noise performance. They concluded that across measures, an increased composite working memory capacity was related to better speech-in-noise performance. They also found

that older listeners with a high working memory capacity were able to perform as well as younger listeners with high working memory capacities, while both younger and older listeners with poorer working memory capacities had poorer abilities to process speech, especially in the presence of background noise (Gordon-Salant & Cole, 2016). Since Gordon-Salant and Cole used both auditory and visual working memory tasks, it is evident that both have an impact on speech-in-noise performance, but since they used a composite score, it is hard to know how much of an impact each separate component had on speech-in-noise performance.

Studies evaluating the relationship between auditory working memory and speech-in-noise performance are rather sparse. A recent study using a frequency matching task to measure auditory working memory found that auditory working memory and speech-in-noise performance are significantly linked in normal hearing listeners (Lad et al., 2020). Another study suggests that auditory working memory and speech-in-noise performance are intrinsically linked, and that working memory drives our perception of sound (Kraus et al., 2012). Both of these studies cite musical training as a factor that improves both auditory working memory skills and speech-in-noise performance (Lad et al., 2020; Kraus et al., 2012). The present study does not specifically measure musical training of participants, but this may explain the variability of these factors amongst normal hearing participants.

The relationship between working memory and speech-in-noise performance has been evaluated many times with various findings, but the relationship between *auditory* working memory and speech-in-noise performance has been shown in recent studies, although sparse. The current study aimed to expand upon our understanding of this connection between auditory working memory and speech-in-noise performance, while also evaluating their relationship with

EHF thresholds. The question evaluated by this study was as follows: How do auditory working memory and EHF thresholds affect the normal-hearer's ability to hear speech-in-noise?

Chapter 2

Methods

This study received approval from the Behavioral and Social Sciences Institutional Review Board at The Ohio State University. Participants who self-reported "normal" hearing were recruited from undergraduate courses in the Department of Speech and Hearing Science. Written consent was provided for participation and release of health information for the purposes of this study. Participants also received compensation for their time in the form of course credit or monetary payment. All testing equipment was calibrated according to the appropriate American National Standards Institute standards (ANSI, 1987, 2018).

Participants

Sixteen participants (9 female, 7 male) took part in this study. Participants ranged from 19-33 years of age (mean age of 22.3). Inclusion criteria included 1) normal otoscopy, 2) pure-tone thresholds within normal limits (symmetric thresholds ≤25 dB HL for 250-8000 Hz), 3) bone conduction thresholds within 10 dB of air conduction thresholds, 4) normal tympanometry (Roup et al., 1998), and 5) present ipsilateral and contralateral acoustic reflexes at 500, 1000, and 2000 Hz. Word recognition in quiet was measured at 50 dB HL for right and left ear using a 50-word list from the Northwestern University Test Number 6 (Tillman & Carhart, 1966). All participants had word recognition in quiet scores greater than or equal to eighty-six percent.

Materials

Adult Auditory Performance Scale:

The Adult Auditory Performance Scale (AAPS; Roup et al., 2021) is a 36-item questionnaire that assesses self-perceived hearing ability. The AAPS presents the participant with six listening environments (noise, ideal, quiet, multiple inputs, auditory

memory/sequencing, and auditory attention span) and they must rate their difficulty hearing in each given environment on a scale from 0 to 6, with 0 meaning never and 6 meaning always. A global AAPS score is based on an average of the responses from all 36 items. Subscale scores are obtained by averaging the responses for each listening condition. Higher global and subscale scores represent greater self-perceived hearing difficulty.

Listening in Spatialized Noise – Sentences (LISN-S):

The Listening in Spatialized Noise – Sentences Test (LiSN-S; Cameron & Dillon, 2007) is a binaural listening task used to assess speech-in-noise perception. The LiSN-S determines the participants speech recognition threshold (SRT) for four different conditions. Each listener's SRT is determined by repeating back a series of target sentences under competing background noise in the form of a children's story. The SRT is determined by the tester entering the number of words correctly recalled per target sentence. This is an adaptive test, so the signal-to-noise ratio (SNR) of the next target sentence is automatically adjusted based on the number of correctly recalled words in the previous sentence. The target sentences are always presented directly ahead at 0 degrees azimuth (using head-related transfer function under headphones) by a female speaker. Masking conditions vary by speaker (same speaker as the target sentences or a different female speaker) and location in reference to the target speaker (either at 0 degrees azimuth or 90 degrees azimuth). This determines the listener's SRT for four target-to-masker conditions – same voice at 0˚ azimuth (SV0, or low cue), same voice at 90 degrees azimuth (SV90), different voice at 0 degrees azimuth (DV0), and different voice at 90 degrees azimuth (DV90, or high cue). These conditions were presented to the listener in the order suggested by Cameron and Dillon (2007): DV90, SV90, DV0, SV0. This allows us to determine the listener's

speech-in-noise perception for multiple environments, as well as three advantage measures: talker, spatial, and total, which explain which factors most affected the listener's SRT.

Word Auditory Recognition & Recall Measure (WARRM):

The Word Auditory Recognition and Recall Measure (WARRM; Smith et al., 2016) was used to measure auditory working memory. Smith et al. (2016) has described the WARRM as an auditory alternative to the visual Reading Span Test (Daneman & Carpenter, 1980). For this task, monosyllabic words are presented binaurally in quiet. The listener is asked to first repeat the word they heard and second judge if the first letter of the word is from the first or second half of the alphabet. A total of 100 words are presented in sets of 2, 3, 4, 5, and 6. At the end of a given set, the listener is prompted by a 500 Hz tone to recall all target words. Set size starts with two words per set, then incrementally increases to six words per set, with five trials per set size. The WARRM yields a word-recognition score, judgement score, and a span score (i.e., auditory working memory). The word-recognition score reflects the percentage of words correctly repeated. The judgement score is based on the percentage of words correctly judged (re: which half of the alphabet the first letter fell into). The span score was calculated based on the largest set size where the participant correctly recalled all words in a set in at least three of the five trials. Partial credit is also added to the recall score if the participant correctly recalls one or two trials for the next largest set size. For the purposes of the current study, span score was also calculated as a percentage score, measuring the percentage of total words correctly recalled.

Procedure

All testing was conducted in a sound-attenuating booth. After confirming inclusion criteria, participant's first completed extended high-frequency threshold testing. Thresholds were measured for 10, 12.5, 14, and 16 kHz using a Grason-Stadler AudioStar and high-frequency

circumaural headphones (Sennheiser HAD 300). The WARRM was presented from a desktop computer and routed through a two-channel audiometer (Grason-Stadler 61) via insert earphones (ER-3A) at 50 dB HL. Participants were instructed to repeat each word, make an alphabetical judgement of the first letter of the word, and recall all words in a set following a tonal cue. The LiSN-S was presented from a computer program routed through an external soundcard via circumaural headphones (Sennheiser HD 215). Participants were instructed to repeat each sentence heard. The number of words correctly repeated was entered into the LiSN-S program. The SNR for each sentence was adaptively determined based on the number of correct words per trial in order to obtain the SRT for each condition. The testing order of the WARRM and LiSN-S were counterbalanced across participants. The AAPS questionnaire was completed during a break between the WARRM and LiSN-S tests to avoid fatigue.

Chapter 3

Results

Descriptive Statistics

Results for most measures were within normal limits across participants, which was expected within this normative sample. Table 1 presents average EHF thresholds. As can be seen in Table 1, EHF thresholds were well within normal limits (≤ 35 dB HL at 10 kHz, ≤ 40 dB HL at 12.5 kHz, ≤50 dB HL at 14 kHz, ≤50 dB HL at 16 kHz; Valiente et al., 2014). Table 2 presents average LiSN-S SRTs. All high cue and low cue SRTs on the LiSN-S were also within normal limits (low cue: (-5.3) – 1.5 for women, (-5.5) – 1.7 for men; high cue: (-20.8) – (-11. 2) for women, (-19.9) – (-11.5) for men; Cameron et al., 2011), with the exception of one participant. This participant had high cue and low cue SRTs that were lower than normal limits, meaning they had poorer-than-average speech-in-noise performance. This participant also had a lower-than-average total advantage, meaning the difference in scores between high cue and low cue conditions was abnormally low. However, this participant had talker and spatial advantages within normal limits (talker: (-0.2) – 11.4 for women, 0.2 – 10.6 for men; spatial: 8.6 – 17.0 for women, 8.4 – 16.8 for men; total: 10 – 18.4 for women, 10.2 – 17.8 for men; Cameron et al., 2011). Table 3 presents average LiSN-S advantage scores. Two participants with normal performance in all LiSN-S conditions had higher-than-normal talker advantages. This means that those two participants perceived more gain than average when there were separate talkers presenting the target sentences and background speech. Scores on the WARRM were much more variable across participants, as seen in Figure 1. The greater variability in WARRM performance resulted in multiple participants falling outside of normal limits (Smith et al., 2016). Specifically,

Frequency	10 kHz	12.5 kHz	14 kHz	16 kHz
Average Threshold	4.07 dB HL	7.04 dB HL	10.16 dB HL	7.82 dB HL
Standard Deviation	11.34	12.71	16.81	17.55

Table 1. Average EHF thresholds across participants in dB HL and one standard deviation. All average thresholds were well within normal limits (Valiente et al., 2014).

Condition	High Cue (DV90)	Low Cue (SV0)
Average LiSN-S SRT	-14.84 dB	-1.75 dB
Standard Deviation	2.00	1.25

Table 2. Average LiSN-S SRT in high cue and low cue conditions across participants and one standard deviation. All average SRTs were well within normal limits (Cameron et al., 2011).

Advantage	Talker	Spatial	Total
Average Score	9.14 dB SNR	11.63 dB SNR	13.11 dB SNR
Standard Deviation	2.18	1.55	1.81

Table 3. Average LiSN-S advantage scores across participants and one standard deviation. All average advantage scores were within normal limits (Cameron et al., 2011).

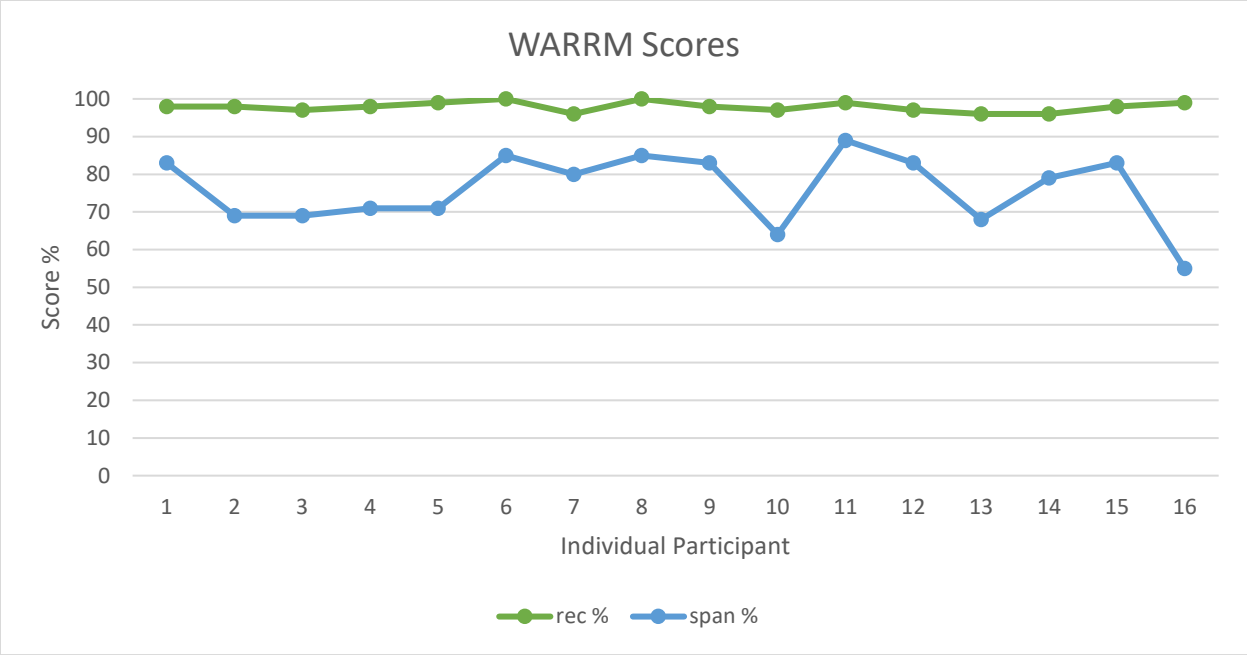

Figure 1. Recognition and span percentage scores for each participant. All recognition scores are at ceiling, with the lowest score being 96%. There is much more variability across span scores, ranging from 55% to 89%.

two of sixteen participants had recognition scores below normal limits (≥96.9%; Smith et al., 2016) and five of sixteen participants had span scores below normal limits (≥70.8%; Smith et al., 2016).

Speech-in-Noise Performance & Extended High-Frequency Hearing

The potential relationships between speech-in-noise performance, EHF thresholds, auditory working memory, and self-perceived hearing abilities were explored using Pearson's correlational analysis. As seen in Figure 2, a significant correlation was seen between EHF thresholds at 12.5 kHz and the LiSN-S talker advantage (r = -0.51; $p < .05$). As thresholds at 12.5 kHz improve, talker advantage on the LiSN-S increases. Better talker advantage scores indicate that listeners had better performance when the two talkers on the LiSN-S have different voices (DV conditions). Other relationships between EHF thresholds and LiSN-S scores were evaluated but were not found to be significant.

Speech-in-Noise Performance & Auditory Working Memory

Trends among auditory working memory and speech-in-noise performance were also observed. Specifically, there was a positive relationship between performance in the high cue condition of the LiSN-S and WARRM span score (r = -0.35; $p > .05$). There was also a positive relationship between performance in the low cue condition of the LiSN-S and WARRM span score (r = -0.22; $p > .05$). As span scores on the WARRM increase, indicating a higher auditory working memory capacity, SRTs in both conditions of the LiSN-S decrease, indicating that the listener can hear target sentences much quieter than the background babble. These trends can be observed in Figure 3 and Figure 4. Although these trends were not strong enough to be

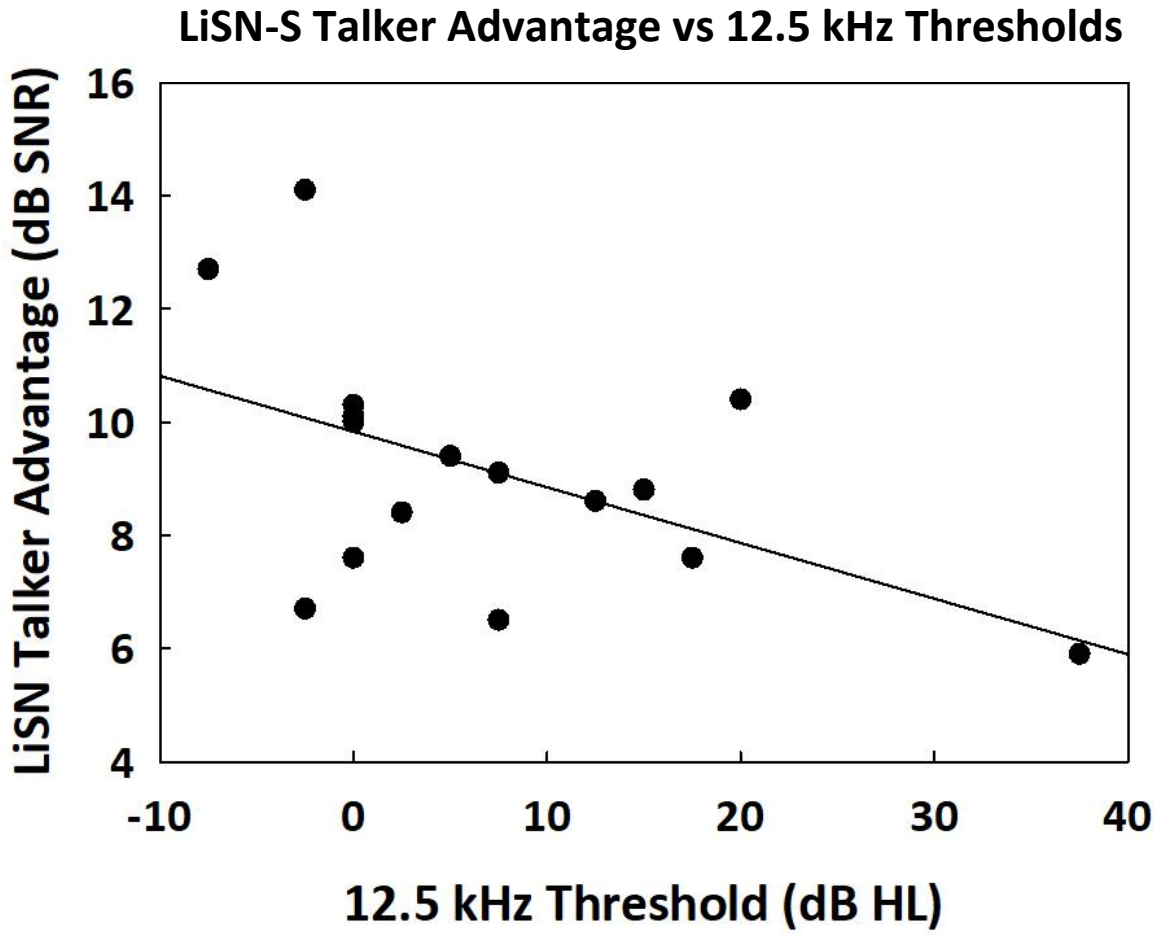

Figure 2. The relationship between EHF thresholds at 12.5 kHz and the LiSN-S talker advantage. As thresholds increase (meaning the signal must be louder for the listener to hear it), talker advantages decrease.

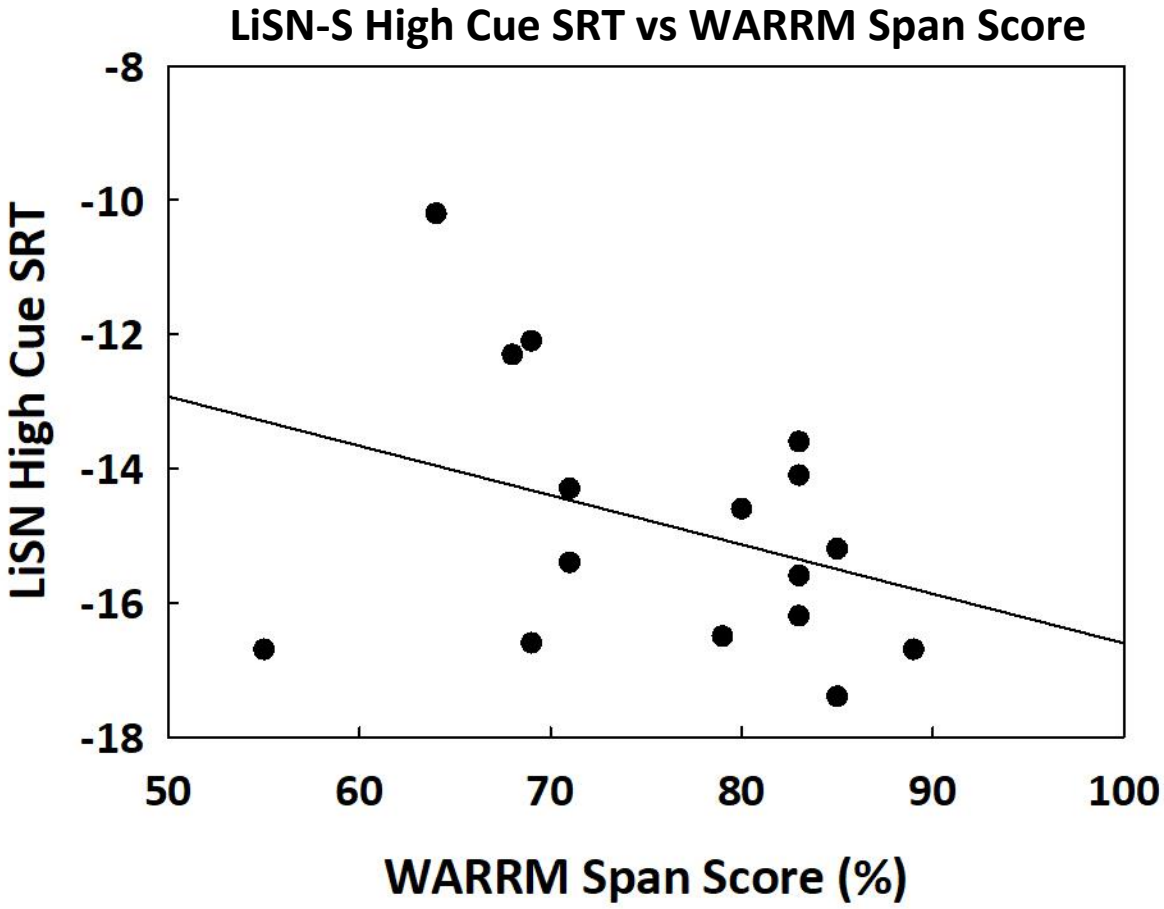

Figure 3. The relationship between LiSN-S high cue SRT and WARRM span score in percentage correct. As span score increases, LiSN-S high cue SRT decreases.

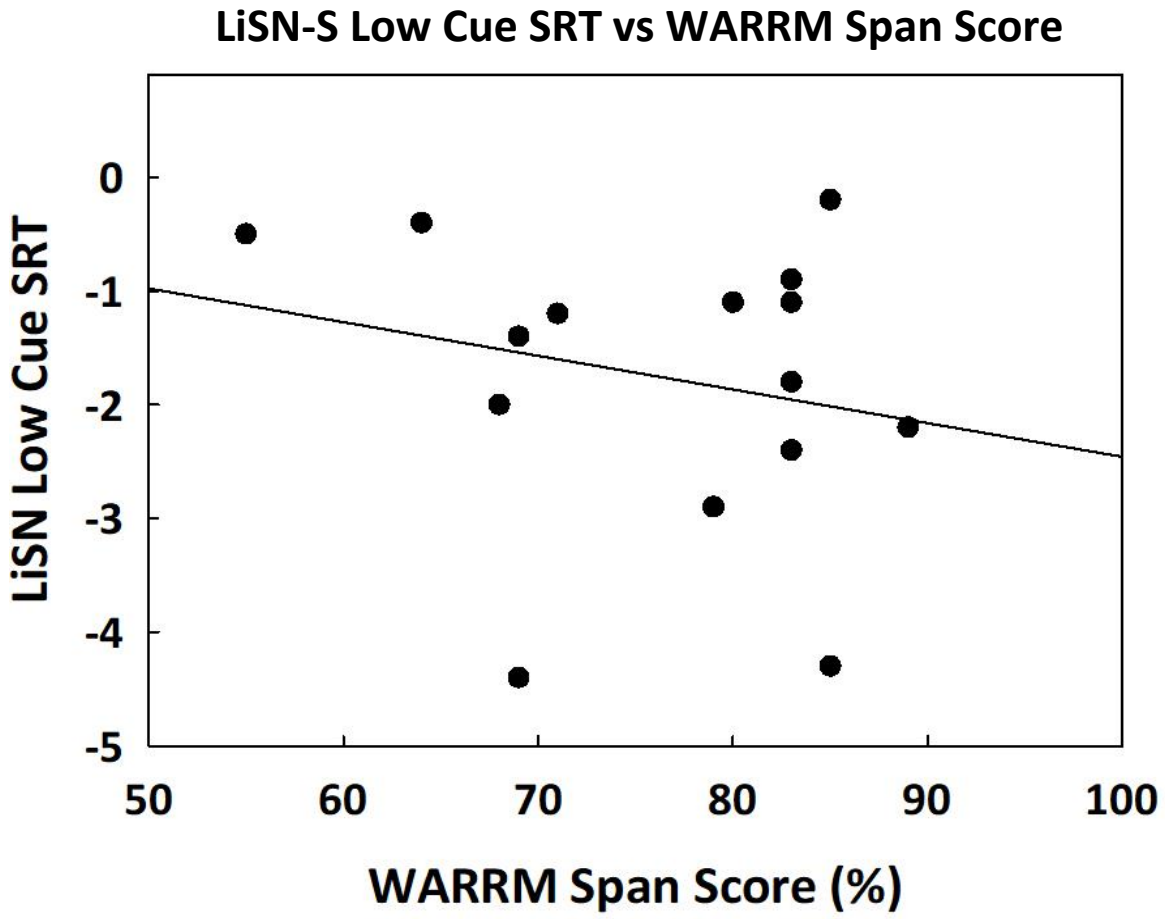

Figure 4. The relationship between LiSN-S low cue SRT and WARRM span score in percentage correct. As span score increases, LiSN-S low cue SRT decreases.

considered significant, it is important to note that there is a trend between auditory working memory and speech-in-noise performance in a normative sample.

Self-Perceived Hearing Ability:

The AAPS was used to assess self-perceived hearing abilities across participants. Scores of thirteen participants were within normal limits, meaning that the participants had average or better-than-average self-perceived hearing abilities. Three participants had two or more subscale scores above normal limits (above the upper 95% confidence interval; Roup et al., 2021), meaning that the participants had poorer-than-average self-perceived hearing abilities for the given listening situation (Roup et al., 2021). Due to counterbalancing of test order, eight participants completed the WARRM before the AAPS and LiSN-S, and eight participants completed the LiSN-S before the AAPS and WARRM. Figure 5 presents average AAPS global and subscale scores as a function of test order. One of the eight participants who completed the WARRM first was not included in this analysis due to their ranking of self-perceived hearing abilities as significantly poorer-than-normal in six out of seven subscales (Roup et al., 2021). As seen in Figure 5, there are observable differences in AAPS scores across groups, specifically in noise and attention, which were ranked poorer amongst participants who completed the LiSN-S before the AAPS, and in memory sequencing and multiple inputs, which were ranked poorer amongst participants who completed the WARRM before the AAPS. This shows that the test that proceeded the AAPS influenced self-perceived hearing ability (i.e., AAPS scores) for at least some of the participants.

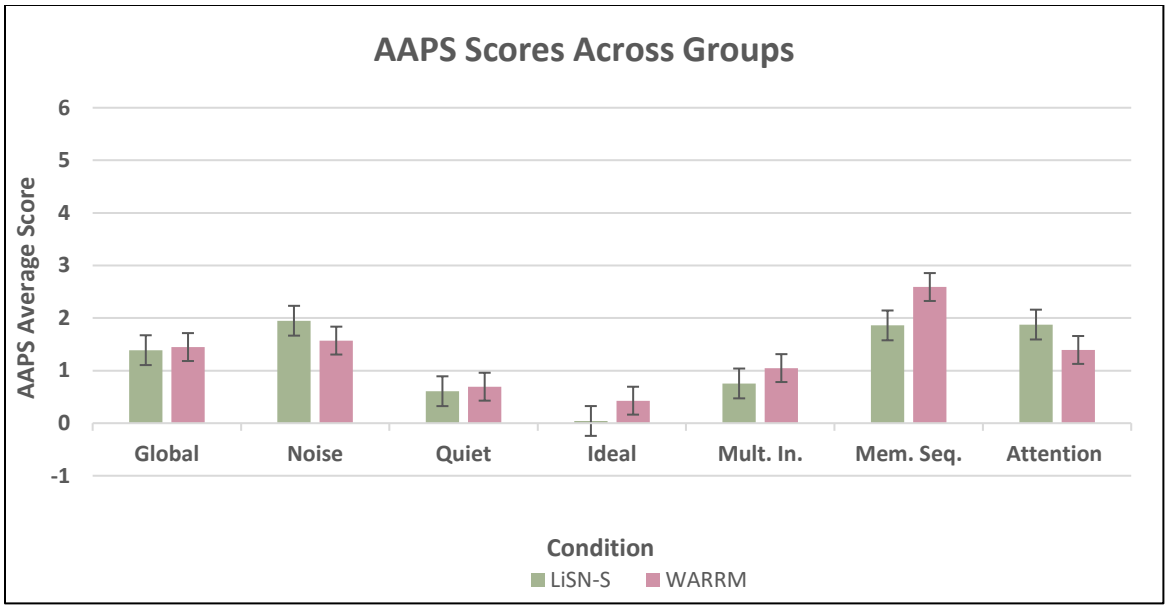

Figure 5. Average AAPS scores across groups. The "LiSN-S" group completed the LiSN-S before the AAPS, and the "WARRM" group completed the WARRM before the AAPS.

Chapter 4

Discussion

The purpose of the present study was to explore the relationship between speech-in-noise performance, auditory working memory, and extended high-frequency hearing abilities in a normative sample. It was hypothesized that poorer EHF thresholds and lower auditory working memory capacity would be associated with poorer speech-in-noise performance. Results revealed a significant relationship between EHF thresholds at 12.5 kHz and the talker advantage on the LiSN-S. This relationship indicates that participants with higher EHF thresholds (i.e., at 12.5 kHz) perceived less benefit in the different voices conditions of the LiSN-S. Although it is expected that listeners perform better in the different voices conditions, this relationship shows that individuals with poorer EHF thresholds were less able to take advantage of talker cues to hear the target sentences in noise. This finding is consistent with the results reported by Yeend et al. (2019) that found that poorer EHF thresholds were correlated with poorer speech-in-noise performance. Yeend et al. (2019) also found that thresholds at 12.5 kHz were most indicative of speech-in-noise performance among young normal hearers in comparison to all other EHF thresholds and averaged EHF thresholds.

The relationship between EHF thresholds and speech-in-noise performance was consistent with the findings of other studies (Badri et al., 2011; Zadeh et al., 2019). Zadeh et al. (2019) found that EHF thresholds could be significant predictors of speech-in-noise performance, such that poorer EHF thresholds were associated with poorer speech-in-noise performance in a young normative sample. Badri et al. (2011) evaluated the relationship between EHF thresholds and speech-in-noise performance in two groups – with and without speech-in-

noise difficulties. Badri et al. (2011) used self-reported ability to hear speech-in-noise and a sentences-in-noise test to determine which participants fell into the category of having speech-in-noise difficulties. The group with speech-in-noise difficulties had poorer EHF thresholds at 12.5 and 14 kHz, suggesting that EHF thresholds could be a marker of speech-in-noise difficulties (Badri et al., 2011). The current study's findings also strengthen the argument that damage to the EHF region of hearing may be the first indication of cochlear damage due to external stressors, which first manifests as speech-in-noise difficulties (Valiente et al., 2014; Borchgrevink et al., 1996). The present study's findings also support the argument made by Yeend et al. (2019), that best clinical practice for a patient with HD and normal clinical thresholds is to test their EHF thresholds to see if there is inflation in thresholds in the EHF region to begin providing answers as to the cause of their speech-in-noise difficulties. As time is often a concern in the clinic, considering the findings by both the current study and Yeend et al. (2019), it may be most time-sensitive to test thresholds at 12.5 kHz, as that provided the strongest link between EHF thresholds and speech-in-noise performance.

Trends were observed between speech-in-noise performance and auditory working memory, although they were not found to be statistically significant. These trends showed a positive relationship between auditory working memory capacity and speech-in-noise performance, such that poorer auditory working memory capacity was associated with poorer speech-in-noise performance. A study by Füllgrabe and Rosen (2016) suggested that speech-in-noise performance and working memory were independent of one another in young, normal-hearing individuals. Füllgrabe and Rosen, however, measured working memory with a reading span task, which measured the visual modality of working memory rather than auditory. As the auditory modality of working memory is believed to be more tightly linked with the auditory

system, it was hypothesized that auditory working memory would be significantly correlated with speech-in-noise performance. There were evident trends that follow this hypothesis among speech-in-noise performance and auditory working memory, which showed correlations between poorer WARRM scores and poorer performance in both high cue and low cue conditions of the LiSN-S. Although these results were not statistically significant, it contests the findings of Füllgrabe and Rosen (2016) and suggests that speech-in-noise performance and working memory may not be completely independent of one another. The trends found in the present study were also consistent with the findings of Gordon-Salant and Cole (2016) who found that poorer working memory capacity and poorer speech-in-noise performance were significantly linked in normal-hearing listeners. Gordon-Salant and Cole (2016) used both a reading span and listening span, evaluating both the visual and auditory modalities of working memory when examining this link.

A study composed by Lad et al. (2020), found that auditory working memory and speech-in-noise performance were significantly linked in young, normal-hearing listeners. However, Lad et al.'s study used a frequency matching task to measure auditory working memory of participants. This was chosen to reveal aspects of phonological working memory, which measures the ability to store a phoneme or tone in working memory rather than a word. In Lad et al.'s (2020) working memory task, the participant heard a tone, then was presented with a second tone which they were instructed to alter until it matched the frequency of the first tone. The present study's test of working memory required the storage of words, as the WARRM required the participant to store a set of words in working memory and later recall them, rather than a frequency matching task, which may explain this slight difference amongst results (Lad et al., 2020). Smith et al. (2016) stressed that it is essential to use an auditory working memory task

containing words when measuring working memory for comparison with speech perception. No significant results were found when using a word-specific auditory working memory task, but there were variations in auditory working memory that followed variations in speech-in-noise performance, albeit within normal limits.

Another finding of the present study was the variation in AAPS scores dependent on when the AAPS was administered. For a subset of participants, self-perceived hearing abilities were influenced by the test that proceeded the AAPS survey. A subset of participants who completed the LiSN-S before the AAPS had inflated scores in noise and attention, meaning their self-perceived speech-in-noise abilities were lower, and they perceived their auditory attention span to be poorer. Similarly, a subset of participants who completed the WARRM before the AAPS had inflated scores in the memory sequencing and multiple inputs subscales. This subset of participants who completed the WARRM before the AAPS had poorer self-perceived ability to hear in conditions with multiple sources of auditory stimulation and a poorer self-perceived ability to remember auditory information. Knowing how the order of test administration influences AAPS scores is very important for future studies, as the AAPS should likely be administered before tests to avoid inflation due to bias after tests that was experienced by some participants.

Limitations

Potential limitations of the present study include the variation in administration of the AAPS and a small sample size. The order of the tests influenced AAPS scores of some participants, although in this normative sample, many results stayed within normal limits (Roup et al., 2021). Additionally, this study included sixteen normal hearing college-aged adults.

Ideally, this study would have a slightly larger sample size to strengthen reliability of results within this sample.

Conclusions and Future Directions

Few significant findings were uncovered in the present study, but it is important to note that this study was done within a normative sample. In a normative sample, it is not necessarily expected that speech-in-noise performance, auditory working memory, and EHF thresholds would be significantly linked if the participants have no speech-in-noise deficits in the first place. However, this study provides a baseline data set of what these connections look like in a normative sample. This data set can be used clinically as a comparative measure for those with HD to look for any differences that may help to explain the cause of HD within this population. Furthermore, if a patient presenting with HD is found to have reduced thresholds in the EHF range, especially at 12.5 kHz, this will allow the clinician to provide answers and make suggestions on EHF hearing conservation before this hearing loss spreads to other regions of the cochlea or further reduces speech-in-noise abilities.

Future research should compare the relationships between speech-in-noise performance, auditory working memory, and EHF thresholds in the population of those struggling with self-perceived HD. The present study provides a baseline data set for those without self-perceived HD, so it is essential to see how these relationships translate to the population of those with HD. Further research on the relationship between HD, auditory working memory, and EHF thresholds may provide clinicians with an answer for those struggling with HD as they can point to deficits in auditory working memory or inflated EHF thresholds as a reason for HD rather than leaving them with no answers and further confusion. This may also allow for counseling on how to

preserve hearing before deficits in the EHF region become worse/spread or referral to therapies to learn strategies to improve auditory working memory.

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