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Speech-in-Noise Assessment in the Routine Audiologic Test Battery: Relationship to Perceived Auditory Disability

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Objectives: Self-assessment of perceived communication difficulty has been used in clinical and research practices for decades. Such questionnaires routinely assess the perceived ability of an individual to understand speech, particularly in background noise. Despite the emphasis on perceived performance in noise, speech recognition in routine audiologic practice is measured by word recognition in quiet (WRQ). Moreover, surprisingly little data exist that compare speech understanding in noise (SIN) abilities to perceived communication difficulty. Here, we address these issues by examining audiometric thresholds, WRQ scores, QuickSIN signal to noise ratio (SNR) loss, and perceived auditory disability as measured by the five questions on the Speech Spatial Questionnaire-12 (SSQ12) devoted to speech understanding (SSQ12-Speech5).

Design: We examined data from 1633 patients who underwent audiometric assessment at the Stanford Ear Institute. All individuals completed the SSQ12 questionnaire, pure-tone audiometry, and speech assessment consisting of ear-specific WRQ, and ear-specific QuickSIN. Only individuals with hearing threshold asymmetries ≤10 dB HL in their high-frequency pure-tone average (HFPTA) were included. Our primary objectives were to (1) examine the relationship between audiometric variables and the SSQ12-Speech5 scores, (2) determine the amount of variance in the SSQ12-Speech5 scores which could be predicted from audiometric variables, and (3) predict which patients were likely to report greater perceived auditory disability according to the SSQ12-Speech5.

Results: Performance on the SSQ12-Speech5 indicated greater perceived auditory disability with more severe degrees of hearing loss and greater QuickSIN SNR loss. Degree of hearing loss and QuickSIN SNR loss were found to account for modest but significant variance in SSQ12-Speech5 scores after accounting for age. In contrast, WRQ scores did not significantly contribute to the predictive power of the model. Degree of hearing loss and QuickSIN SNR loss were also found to have moderate diagnostic accuracy for determining which patients were likely to report SSQ12-Speech5 scores indicating greater perceived auditory disability.

Conclusions: Taken together, these data indicate that audiometric factors including degree of hearing loss (i.e., HFPTA) and QuickSIN SNR loss are predictive of SSQ12-Speech5 scores, though notable variance remains unaccounted for after considering these factors. HFPTA and QuickSIN SNR loss—but not WRQ scores—accounted for a significant amount of variance in SSQ12-Speech5 scores and were largely effective at predicting which patients are likely to report greater perceived auditory disability on the SSQ12-Speech5. This provides further evidence for the notion that speech-in-noise measures have greater clinical utility than WRQ in most instances as they relate more closely to measures of perceived auditory disability.

Key words: Patient handicap, Speech-in-noise, SSQ, Word recognition.

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INTRODUCTION

Self-assessment of perceived communication ability in patients with hearing loss has been a topic of interest for decades, with questionnaires being used since the onset of audiology (Davis 1948; High et al. 1964). Several reasons have been put forth as to why self-assessment of hearing handicap is thought to be meaningful in both research and clinical practices. For example, self-assessment scales have been suggested to have the potential to assess perceived function in real-world listening environments that cannot be easily replicated within laboratory or clinical scenarios (Cox 2003). They have also been consistently utilized as an outcome measure after fitting of hearing aids, osseointegrated devices, or cochlear implants (Noble & Gatehouse 2006; Dillon et al. 2017; Snapp et al. 2017). Self-perception of hearing ability has also been shown to predict which patients are likely to pursue amplification (Palmer et al. 2009), and self-assessment scales have also demonstrated that patients with higher degrees of autonomous motivation were more likely to pursue help for hearing difficulties (Ridgway et al. 2017). Lastly, self-assessment scales have the advantage of being extremely versatile, and in the audiologic community have not only been utilized to assess the impact of hearing loss or hearing aids, but also the effect of other symptoms such as dizziness (Jacobson & Newman 1990) and tinnitus (Newman et al. 1996; Henry et al. 2016).

While there are a number of self-assessment questionnaires, most of them ask individuals to rate their perceived difficulties in challenging listening situations. This occurs in part because even the earliest assessments showed little relationship between speech understanding in quiet and perceived communication abilities in daily listening environments (Davis 1948; High et al. 1964; Giolas et al. 1979). For these reasons, the most widely used measures in clinical audiology today focus predominately on understanding speech-in-noise, rather than in quiet. For example, the Hearing Handicap Inventory in Adults and Elderly ask patients to rate their perceived handicap in several environments which often involve background noise (Newman et al. 1990, 1991, 1993). The abbreviated profile of hearing aid benefit (Cox & Alexander 1995; Cox 2003) devotes entire subsections to the ability of the patient understanding speech in background noise. Last, the Speech Spatial Questionnaire (SSQ; Gatehouse & Noble 2004) devotes multiple questions toward the patients' perceived ability to understand speech-in-noise, and considers

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speech understanding in noise one of the key domains for interpreting the SSQ. Notably, screening versions or short versions of the SSQ all are based on questions related to speech understanding in some sort of background noise (Demeester et al. 2012; Noble et al. 2013; Moulin et al. 2019).

In recent years, the SSQ has been increasingly used to assess perceived auditory disability, and outcomes after intervention with hearing aids or implantable devices (Noble & Gatehouse 2006; Dillon et al. 2017; Snapp et al. 2017). The SSQ has been widely used to date because of its ease of use, and its capacity to examine not only perceived speech recognition in adverse listening environments, but deficits related to sound localization and sound quality. Global ratings on the SSQ appear to be somewhat related to the degree of hearing loss, as a moderate correlation (0.51) between 4-frequency pure-tone average (PTA) and SSQ average was observed in 153 patients (Gatehouse & Noble 2004). These same authors subsequently demonstrated that patients with interaural hearing asymmetries >10 dB had lower SSQ scores on average than those with symmetric hearing thresholds (Noble & Gatehouse 2004). The SSQ was subsequently demonstrated to show good test-retest correlation in older adults with normal hearing, with the strongest correlations observed when presented via interview with a trained professional, and weaker correlations when the SSQ was returned by mail (Singh & Kathleen Pichora-Fuller 2010). A later investigation with 216 individuals reported that the biggest sources of variance on the SSQ were the degree of hearing loss in the better-hearing ear, and the presence of hearing-loss asymmetry (Moulin & Richard 2016). These same authors also reported smaller effects of age on the “Speech” subscale, and the number of years of education was associated with ratings on some questions in the “Spatial” and “Qualities” subscales (Moulin & Richard 2016).

Because of the time required to complete the 49-item full SSQ, several investigators have generated shorter versions of the SSQ for clinical or screening use. For example, the 49-item SSQ was shortened to a 12-item screening version (SSQ12) for clinical use by taking the 12 questions which yielded the greatest difference in scores between individuals with hearing loss and those with normal hearing (Noble et al. 2013). A 5-item version was also generated by cluster analysis on the 49-item SSQ, and was shown to be better than asking a patient “Do you have hearing loss?” at obtaining an initial impression of hearing disability (Demeester et al. 2012). Last, a 15-item SSQ was generated and validated with the specific goal of maintaining the three subscales of the SSQ (Moulin et al. 2019); previous short versions of the SSQ were not explicitly designed with this goal in mind.

One surprising aspect of self-assessment of perceived patient disability with the SSQ and other questionnaires is that very little is known as to how measured speech-recognition abilities are related to perceived patient disability. For example, the relationship between speech-in noise (SIN) abilities measured explicitly and questionnaire-based ratings has not been directly explored with the SSQ. A closely related investigation reported that the wave offset latency and waveform morphology of the speech-evoked auditory brainstem response was more predictive of SSQ ratings than the QuickSIN SNR loss or the audiometric thresholds (Anderson et al. 2013). While compelling, it is worth noting that the average audiometric threshold of the participants in this study had normal hearing through 4 kHz, with no individuals having audiometric thresholds >40 dB HL in this frequency region. Moreover, visual inspection of their data suggests that less than 4% of their cohort had QuickSIN SNR losses >3 dB, which is reported to be the dividing line between normal performance and a SIN deficit according to the QuickSIN manual. Thus, while these authors noted little relationship between SSQ rating and hearing acuity or QuickSIN SNR loss, this lack of this relationship may have simply reflected the relatively restricted and largely normal range of hearing thresholds and QuickSIN losses in their sample. A separate investigation measured percent correct on a SIN test, as well as the Iranian version of the SSQ in groups of younger and older adults with normal hearing. These authors observed significant effects of age on both measures, but did not report how SIN and SSQ performance were related (Heidari et al. 2018). Using a similar approach focused on spatial hearing, a different group of authors reported lower QuickSIN SNR losses and SSQ ratings in older than younger adults with normal hearing, but once again did not report the relationship between performance on these measures (Adel Ghahraman et al. 2020).

Taken together, these studies cannot address the question of how SIN abilities, hearing acuity, and perceived auditory disability interact in a group of patients with a wide array of hearing losses that are representative of clinical practice. Moreover, they fail to address the relationship between perceived disability and speech recognition in quiet. The latter aspect is particularly relevant, as it directly relates to current clinical practice in which monosyllabic word recognition has been the default test of speech perception in routine audiometric testing since the inception of audiology. Thus, the primary test of speech recognition used in audiologic practice is inconsistent with the questionnaires used to assess perceived auditory disability. We have argued that speech-in-noise could replace word recognition in quiet (WRQ) as the default test of speech recognition in most patients (Fitzgerald et al. 2023). A useful step toward substantiating that goal would be to determine that questionnaires such as the SSQ12 which attempt to measure perceived auditory disability are more closely related to speech understanding in noise than quiet. Here, we examined these issues by pursuing the following three objectives. First, we characterized the relationship between the ratings on the five questions on the SSQ12 that relate to speech understanding (defined here as the SSQ12-Speech5), and key audiometric variables including degree of hearing loss, WRQ using NU-6 words (Tillman & Carhart 1966), and QuickSIN SNR loss (Killion et al. 2004). Second, we examined the amount of variance in SSQ12-Speech5 scores that is accounted for by age, degree of hearing loss, WRQ, and QuickSIN SNR loss. Last, we assessed the extent to which age, degree of hearing loss, WRQ, and QuickSIN SNR loss predict which patients reported a perceived auditory disability as measured by the SSQ12-Speech5 (i.e., SSQ12-Speech5 score <6.83). Here, we addressed these issues by examining data from 1633 patients seen at Stanford University who completed the SSQ12 as well as pure-tone audiometry, WRQ, and QuickSIN in each ear.

MATERIALS AND METHODS

Participants

All participants consisted of patients undergoing audiometric assessments at the Stanford Ear Institute between 2017 and

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2020. Here, we only included data from patients who completed the SSQ12 questionnaire, ear-specific WRQ and QuickSIN, and whose hearing thresholds were symmetric. Here, we define symmetric hearing thresholds as having an asymmetry in high-frequency PTA (HFPTA; average of air conduction thresholds at 1, 2, and 4 kHz) of less than 10 dB HL (Noble & Gatehouse 2004). The HFPTA was chosen because it has been reported to relate more closely to measures of speech recognition than the traditional PTA (Wilson 2011), and because the HFPTA, in conjunction with the QuickSIN SNR loss, can predict patients with good word recognition scores in quiet (Fitzgerald et al. 2023). A total of 1633 patients met these criteria and were included for subsequent analysis (49.9% female). The age of patients in this sample ranged from 18 to 104 years of age; children under the age of 18 were excluded from this study to avoid developmental effects observed with performance on some tests of speech-in-noise (Holder et al. 2016). These patients were often seen in conjunction with otologists and neurotologists, and thus may have a wide array of auditory pathologies (see also Fitzgerald et al. 2023). Last, 3.6% of the patients in this dataset had a conductive component greater than 10 dB in at least one ear. Demographic information for this sample is provided in Table 1.

Procedures

All data were obtained as part of routine clinical audiologic evaluations at the Stanford Ear Institute. These evaluations consisted of the traditional audiologic test battery (otoscopy, tympanometry and acoustic reflex measurements, air conduction and bone conduction thresholds, speech-reception threshold, and WRQ). Air conduction and bone conduction thresholds were obtained using the modified Hughson–Westlake method (Carhart & Jerger 1959). Inter-octave thresholds at 3000 and 6000 Hz were regularly obtained; other inter-octave thresholds were measured when the thresholds differed by ≥20 dB HL between neighboring octaves. Some individuals also underwent additional testing, such as otoacoustic emissions, vestibular assessment, and auditory brainstem responses. Those data are not considered here. All audiologic testing was completed in double-walled sound booths using GSI-61 (Grayson-Stadler) audiometers and either ER-3A insert earphones or circumaural headphones (Sennheiser HD 200).

We obtained WRQ scores using NU-6 lists (Tillman & Carhart 1966), and SIN abilities using the QuickSIN (Killion et al. 2004). WRQ scores were obtained unilaterally in each ear. In most cases, 25-word were used to obtain WRQ. In some instances, the difficulty-weighted words were used (Hurley & Sells 2003), and if a patient scored either 90% or 100% across the first 10 words, then word recognition was discontinued. Regardless of the number of presentations, we computed the percentage of words correctly repeated by the patient and reported that as their WRQ score. Following measurement of WRQ, QuickSIN SNR losses were measured in each ear. Two lists were presented for each condition. In each condition, the QuickSIN SNR loss was the average SNR loss of those two lists. Note that unlike the WRQ scores, the QuickSIN SNR losses reflect dB SNR necessary to repeat 50% correct identification of key words in that sentence relative to a group of controls with normal hearing.

TABLE 1. Demographic information

	Mean	Median	Range
Sex	49.9% female		
Age (yrs)	54.8	57	18–104
HFPTA (dB HL)	19.6	15	–5 to 110

HFPTA, high-frequency pure-tone average.

To minimize effects related to presentation level, we utilized the same level for both WRQ and QuickSIN testing for each patient. The default presentation level was 70 dB HL unless that level would have resulted in some part of the signal being inaudible. In that case, the audiologist increased the signal presentation level to maximize audibility while not exceeding the uncomfortable loudness level of the patient. In this way, we attempted to observe the best possible performance for a given individual (PBmax for WRQ measures). Approximately 84% of patients were tested at the default level of 70 dB HL. In all patients, we used recorded stimuli for the speech material.

Perceived auditory disability was measured by the SSQ12 (Noble et al. 2013). We selected the SSQ12 because it is a short version of the full SSQ and was designed to be appropriate for clinical use (Noble et al. 2013). The SSQ12 was given to patients who were scheduled for an audiogram; all questionnaires were provided by a member of the front-desk staff. Patients were instructed to base their ratings on their unaided hearing if they wore hearing aids regularly. Patients subsequently filled out the questionnaire while waiting for their appointment with their audiologist. Thus, the questionnaires were self-administered, with no input from an audiologist or other professional. Responses for each of the 12 questions were then entered into a database by the patient's audiologist. Data from incomplete questionnaires were not included in the data analysis, leaving 1633 patients who completed the full audiometric test battery and the SSQ12.

Data Analysis

One challenge with examining SSQ12 performance is that the patient ratings that comprise the SSQ12 are based on input from both ears. In contrast, audiometric assessment is individual-ear specific, including the audiometric thresholds, WRQ scores, and QuickSIN SNR losses measured here. To address this issue, we restricted our analysis of audiometric data to only include individuals with symmetric hearing abilities, and only included audiometric data from the better-hearing ear. We defined symmetric hearing as having HFPTA values that differed by less than 10 dB HL between ears. We chose these two variables for analysis, because hearing thresholds in the better-hearing ear and between-ear asymmetries have been shown to account for the largest sources of variance in SSQ scores in individuals with both normal hearing and hearing loss (Moulin & Richard 2016). We then averaged the ratings of questions 1 to 5 on the SSQ12 to obtain the SSQ12-Speech5 score, as questions 1 to 5 on the SSQ12 all address speech perception in noise or competing talkers. We chose to average scores for these questions together into a single rating because of strong internal consistency as indicated by a Cronbach α value of 0.928.

Our first goal was to examine SSQ12-Speech5 scores as a function of HFPTA, WRQ scores, and QuickSIN SNR loss. For each of these values, we stratified performance into categories widely used in audiologic practice. HFPTA values were stratified

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as follows: <15, 16 to 25, 26 to 40, 41 to 55, 56 to 70, and 70+ dB HL (Goodman 1965). These categories are widely known as normal hearing, borderline normal, mild, moderate, moderately severe, and severe to profound hearing loss, respectively. WRQ scores were stratified into three categories: 88 to 100%, 76 to 87%, and <76%. These categories are defined here as excellent, good, and fair-to-poor, respectively. We selected these categories because, for a 25-word list, scores between 88 and 100% do not differ statistically (Carney & Schlauch 2007), while 76% is often used anecdotally by audiologists to separate "good" from "fair" word recognition abilities (Lawson & Peterson 2012). These categories are the same as those used in Fitzgerald et al. (2023). Last, QuickSIN SNR losses were stratified into four categories: −3.5 to 3, 3.5 to 6.5, 7 to 14.5, and ≥15 dB SNR loss. According to the QuickSIN manual, these four categories correspond to normal, mild, moderate, and severe SNR losses, respectively (Etymotic Research 2006). For each of these three stratified factors, a one-way analysis of variance was completed with SSQ12-Speech5 scores as the dependent variable. Significant main effects were followed by post-hoc Holm–Sidek comparisons. As a final step toward examining the influence of each factor on SSQ12-Speech5 scores, we treated each factor as a continuous variable, and conducted individual linear regression analyses for HFPTA, WRQ score, and QuickSIN SNR loss with SSQ12-Speech5 scores as the dependent variable.

In our second analysis, a multiple regression analysis was used to evaluate the amount of variance in SSQ12-Speech5 scores uniquely accounted for by patient age, HFPTA, WRQ score, and QuickSIN SNR loss.

In our final analysis, a logistic regression analysis was used to assess the utility of age, HFPTA, WRQ score, and QuickSIN SNR loss in predicting "good" versus "poor" SSQ12-Speech5 scores, as defined by SSQ12-Speech5 scores ≥6.83 and <6.83, respectively. We chose 6.83 as the cutoff value as it is 2 SDs lower than the mean SSQ value obtained from 103 young adults with normal hearing (Demeester et al. 2012). For each of these factors, we additionally quantified sensitivity, specificity, and area under the curve (AUC) for predicting whether a patient's SSQ12-Speech5 score is greater or less than 6.83. All data, statistical analyses, and code for plotting of figures for this study are publicly available through the Stanford University data repository.

RESULTS

Relationship Between Individual Factors and SSQ12-Speech5 Scores

Results indicate HFPTA, WRQ scores, and QuickSIN scores significantly relate to SSQ12-Speech5 scores in our sample of 1633 adult patients. The left panel of Figure 1 shows SSQ12-Speech5 scores for 1633 patients as a function of HFPTA in their better-hearing ears. Results of a one-way analysis of variance showed a significant decrease in SSQ12-Speech5 scores, indicating greater perceived auditory disability with more severe degrees of hearing loss ($F_{5,1626} = 105.6$, $p < 0.001$). Post-hoc Holm–Sidek tests revealed significant reductions in SSQ12-Speech5 scores with each degree of decreasing hearing loss from normal hearing (<15 dB HL) to moderately severe losses (56 to 70 dB HL; $p < 0.05$ in each case). SSQ12-Speech5 scores did not differ, however, between patients with moderately severe and severe-profound losses ($p = 0.55$). Table 2 shows the mean, median, and range of SSQ12 speech scores for each degree of hearing loss. The right panel of Figure 1 displays individual SSQ12-Speech5 scores as a function of HFPTA as a continuous variable. A linear regression analysis revealed a significant relationship between HFPTA and SSQ12-Speech5 score ($F_{1,1628} = 607.6$, $p < 0.001$). HFPTA was shown to account for 27% of the variance in SSQ12-Speech5 scores ($R^2 = 0.27$).

Similar relationships are shown for QuickSIN SNR losses and WRQ scores. Here, SSQ12-Speech5 scores decreased significantly with degree of SNR loss (see left panel of Fig. 2; $p < 0.001$); post-hoc Holm–Sidek tests revealed significant differences in SSQ12-Speech5 scores for each successive degree of SNR loss ($p < 0.001$ in each case). A linear regression also revealed a significant relationship between QuickSIN SNR loss and SSQ-Speech5 scores, with this variable accounting for 25%

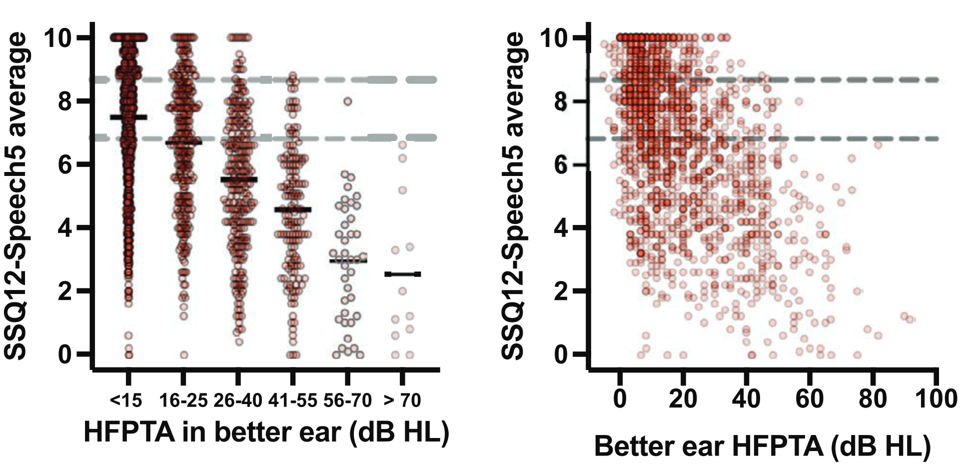

Fig. 1. SSQ12-Speech5 scores as a function of HFPTA for 1633 patients. In both panels, each circle reflects an individual data point. To minimize the effects of overplotting, darker shading reflects values with more data points, while lighter shading reflects values with fewer data. The top dashed gray line reflects the mean SSQ12-Speech5 rating from normal-hearing young adults. The bottom dashed gray line is 2 SDs worse than that point. The left panel breaks HFPTA into varying degrees of hearing loss. For each degree of hearing loss, mean performance is marked by the solid black line. In the right panel, HFPTA is treated as a continuous variable, and the dashed black line reflects a linear regression fit to these data. HFPTA indicates high-frequency pure-tone average; SSQ12, Speech Spatial Questionnaire-12.

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TABLE 2. Mean, median, and the range of SSQ12-Speech5 scores for varying degrees of hearing loss

HFPTA (dB HL)	Mean SSQ12-Speech5 Score	Median SSQ12-Speech5 Score	Range of SSQ12-Speech5 Scores
Normal (≤15 dB HL)	7.50	8.00	0.00–10.00
Normal (16–25 dB HL)	6.69	7.00	0.00–10.00
Mild (26–40 dB HL)	5.51	5.60	0.00–10.00
Moderate (41–55 dB HL)	4.58	4.55	0.00–8.00
Moderately severe (56–70 dB HL)	2.97	3.00	0.00–8.00
Severe to profound (≥71 dB HL)	2.76	2.00	0.00–6.60

HFPTA, high-frequency pure-tone average; SSQ12, Speech Spatial Questionnaire-12.

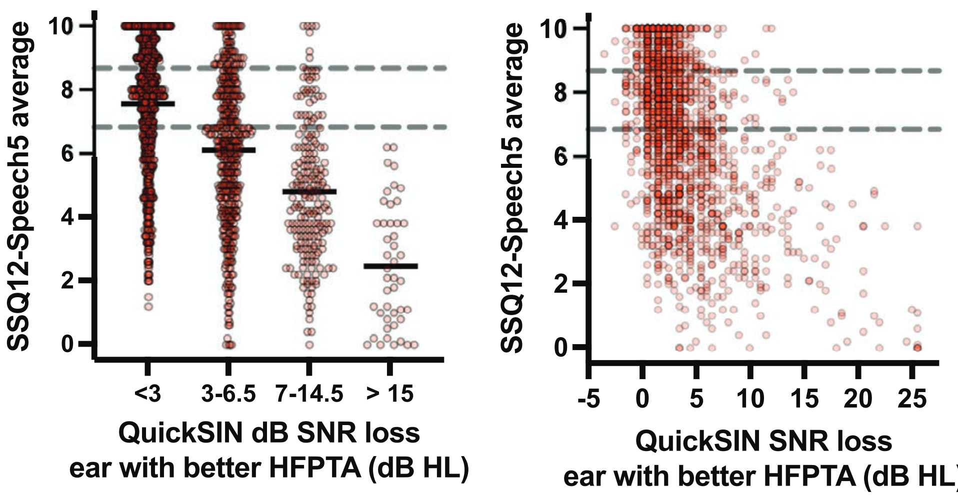

Fig. 2. SSQ12-Speech5 scores as a function of QuickSIN SNR loss for 1633 patients. In both panels, each circle reflects an individual data point. To minimize the effects of overplotting, darker shading reflects values with more data points, while lighter shading reflects values with fewer data. The top dashed gray line reflects the mean SSQ12-Speech5 rating from normal-hearing young adults. The bottom dashed gray line is 2 SDs worse than that point. The left panel breaks QuickSIN SNR loss into different categories according to the QuickSIN manual. For each category of SNR loss, mean performance is marked by the solid black line. In the right panel, QuickSIN SNR loss is treated as a continuous variable, and the dashed black line reflects a linear regression fit to these data. SIN indicates speech understanding in noise; SNR, signal to noise ratio; SSQ12, Speech Spatial Questionnaire-12.

of the variance in SSQ12-Speech5 scores (right panel of Fig. 2; $F_{1,2081}$ = 458.7, p < 0.001; R^2 = 0.25). Last, SSQ12-Speech5 scores also decreased significantly with categories of WRQ scores (see left panel of Fig. 3; $p \leq 0.013$), with all categories of WRQ scores being significantly different from one another (p < 0.05 in each case). As with HFPTA and QuickSIN SNR loss, a linear regression revealed a significant relationship between WRQ score and SSQ12-Speech5 score (right panel of Fig. 3, $F_{1,2084}$ = 214.7, p < 0.001) Notably, WRQ scores accounted for less variance in SSQ12-Speech5 scores (R^2 = 0.13) than either HFPTA or QuickSIN SNR loss.

Combined Sources of Variance in SSQ-Speech5 Scores

A multiple regression analysis was conducted to assess the amount of variance in SSQ12-Speech5 score accounted for by age, HFPTA, WRQ score, and QuickSIN SNR loss combined. A correlation matrix for all variables included in the model is displayed in Table 3. When considered together, age, HFPTA, WRQ score, and QuickSIN SNR loss accounted for 30.5% of the variance in SSQ12-Speech5 score ($F_{4,1625}$ = 179.7, p < 0.001). Removing WRQ score from the model did not significantly change the amount of variance accounted for in SSQ12-Speech5 score ($F_{1,1625}$ = 0.45, p = 0.5). Removing HFPTA or QuickSIN SNR loss from the model, however, significantly reduced the amount of variance in SSQ12-Speech5 score accounted for by audiometric variables (HFPTA: $F_{1,1625}$ = 130.07, p < 0.001; QuickSIN SNR Loss: $F_{1,1625}$ = 63.91, p < 0.001). Together, these findings suggest that a patient's audibility and ability to understand speech-in-noise —but not in quiet—significantly contribute to their perceived auditory disability after accounting for age.

Predicting Categories of SSQ12-Speech5 Scores

In addition to the linear regression analyses described earlier, a logistic regression analysis was used to examine the extent to which "good" versus "poor" SSQ12-Speech5 scores can be predicted based on demographic and audiometric factors. Using data from young adults with normal hearing (Demeester et al. 2012), SSQ12-Speech5 scores were categorized as "good" or "poor," with scores falling in the "poor" range indicative of greater perceived auditory disability. "Good" scores, indicating less perceived auditory disability, were defined as a mean SSQ12-Speech5 score ≥6.83, as these values were within 2 SD of the normative data from Demeester et al. (2012). In contrast, "poor" SSQ12-Speech5 scores were defined as ≤6.83 as they were greater than 2 SD from the normative data from Demeester et al. Age, HFPTA, WRQ score, and QuickSIN SNR loss were included as predictor variables in the model. Of these variables, only HFPTA (z = −8.48, p < 0.001), QuickSIN SNR loss (z = −7.06, p < 0.001), and age (z = 2.12, p < 0.05) were found to significantly predict whether patients' SSQ12-Speech5 scores fell within the "good" versus

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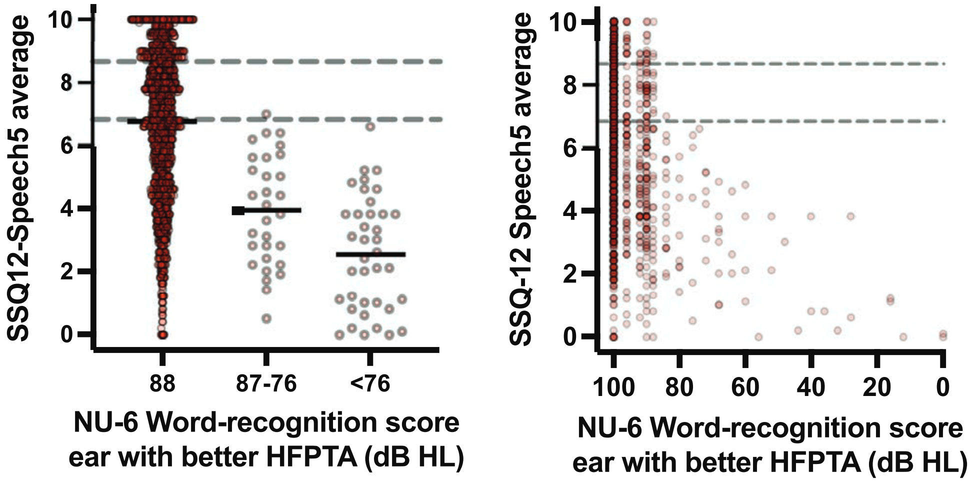

Fig. 3. SSQ12-Speech5 scores as a function of word-recognition scores in quiet for 1633 patients. In both panels, each circle reflects an individual data point. To minimize the effects of overplotting, darker shading reflects values with more data points, while lighter shading reflects values with fewer data. The top dashed gray line reflects the mean SSQ12-Speech5 rating from normal-hearing young adults. The bottom dashed gray line is 2 SDs worse than that point. The left panel breaks word recognition scores into different categories according to their performance. For each category of word-recognition score, mean performance is marked by the solid black line. In the right panel, word-recognition scores are treated as a continuous variable, and the dashed black line reflects a linear regression fit to these data. SSQ12 indicates Speech Spatial Questionnaire-12.

TABLE 3. Correlation matrix for multiple regression analyses

	Age	HFPTA	WRQ	QuickSIN SNR Loss	SSQ12-Speech5 Score
Age	—	0.609	−0.271	0.484	−0.283
HFPTA	0.609	—	−0.576	0.717	−0.521
WRQ	−0.271	−0.576	—	−0.681	0.366
QuickSIN SNR loss	0.484	0.717	−0.681	—	−0.497
SSQ12-Speech5 score	−0.283	−0.521	0.366	−0.497	—

HFPTA, high-frequency pure-tone average; SIN, speech understanding in noise; SNR, signal to noise ratio; SSQ12, Speech Spatial Questionnaire-12; WRQ, word recognition in quiet.

"poor" range. In contrast, WRQ score ($z = 0.38$, $p = 0.70$) was not a significant predictor of whether a patient was likely to report greater perceived auditory disability according to the SSQ12-Speech5.

To further explore the sensitivity and specificity of HFPTA and QuickSIN SNR loss as predictors of "good" versus "poor" SSQ12-Speech5 scores, receiver operating characteristic curves were generated for each of these variables. The sensitivity, specificity, and AUC are depicted in Table 4. Both HFPTA and QuickSIN SNR loss were found to have moderate diagnostic accuracy for SSQ12-Speech5 scores as demonstrated by AUC values of 0.747 and 0.739, respectively, with a combined AUC of 0.77. The sensitivity with which "good" versus "poor" SSQ12-Speech5 scores could be identified based on HFPTA and/or QuickSIN SNR loss ranged from 66.79 to 92% with specificity ranging from 57.51 to 68.78% (Table 4). The greatest sensitivity for predicting patients with "poor" SSQ12-Speech5 scores was observed when deficits in HFPTA and/or QuickSIN SNR loss fell within the "moderate" or greater range. Specifically, HFPTA ≥40 resulted in 88.26% sensitivity as compared with 77.36% for HFTPA ≥25. Similarly, QuickSIN SNR loss ≥7 yielded 84.96% sensitivity as opposed to 66.79% sensitivity for QuickSIN SNR loss ≥3. Together, knowing that a patient's HFPTA ≥40 and QuickSIN SNR loss ≥7 provides an even stronger indicator of a "poor" SSQ12-Speech5 score for that patient with a combined sensitivity of 92%. However, the specificity of each of these measures is moderate at best, suggesting that many individuals with better-hearing sensitivity and/or speech-in-noise abilities reported a perceived deficit understanding speech-in-noise relative to young adults with normal hearing. Overall, these results suggest that unaided hearing sensitivity and speech-in-noise abilities provide useful predictive power in determining perceived auditory disability as measured by the SSQ12-Speech5.

TABLE 4. Audiometric criterion and the corresponding sensitivity and specificity values for predicting patients with poor SSQ12-Speech5 scores

Criterion	Sensitivity	Specificity
HFPTA ≥25	77.36%	64.10%
QuickSIN ≥3	66.79%	68.78%
HFPTA ≥25 and QuickSIN ≥3	82.59%	71.76%
HFPTA ≥40	88.26%	57.57%
QuickSIN ≥7	84.96%	57.51%
HFPTA >40 and QuickSIN ≥7	92.00%	59.50%

HFPTA, high-frequency pure-tone average; SIN, speech understanding in noise; SSQ12, Speech Spatial Questionnaire-12.

DISCUSSION

Taken together, our results indicate that average SSQ12-Speech5 scores decrease with greater degrees of hearing loss, greater QuickSIN SNR loss, and poorer WRQ scores. However,

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considerable between-patient variability was noted across all these measures, and the ability of these audiometric variables to predict SSQ12-Speech5 scores was relatively poor. Notably, only HFPTA, QuickSIN SNR loss, and age accounted for significant variance in SSQ12-Speech5 scores. Removing WRQ scores from the statistical model did not significantly change the amount of variance in SSQ12-Speech5 scores accounted for, suggesting that word recognition scores in quiet provide little to no information on perceived auditory disability as measured by the SSQ12-Speech5. Last, while QuickSIN SNR loss and HFPTA were relatively poor at predicting raw SSQ12-Speech5 scores, they were reasonably accurate at predicting which individuals were likely to have SSQ12-Speech5 scores suggestive of greater perceived auditory disability. However, both measures had relatively poor specificity, suggesting that some individuals reported difficulty understanding speech-in-noise despite having normal HFPTA or QuickSIN SNR losses. To our knowledge, this is the first large-scale measurement that compared SIN performance with perceived auditory disability. As such, these data have implications for interpretation of questionnaires such as the SSQ12, and for clinical measurement of speech-recognition abilities.

Our data, obtained from a hospital practice, are consistent with several other studies indicating that decreases in hearing threshold are on average associated with lower SSQ12 scores (Gatehouse & Noble 2004; Noble et al. 2012, 2013; Moulin & Richard 2016; Moulin et al. 2019). Here, we build on this previous work by demonstrating that decreasing speech-in-noise abilities as measured by the QuickSIN are also on average associated with lower SSQ12-Speech5 scores. This is a useful validation for questionnaire-based measures, and it is noteworthy that QuickSIN SNR losses have similar predictive power to degree of hearing loss when accounting for variance in SSQ12-Speech5 scores. Despite these clear trends in how changes in HFPTA or QuickSIN influence the mean SSQ12-Speech5 scores, these key audiometric measures, even when combined with age or traditional measures of WRQ, predicted only a small amount of variance in the raw SSQ12-Speech5 scores. We speculate there are several factors that contribute to this relatively low predictive power.

First and most important, the SSQ12-Speech5 scores themselves show exceedingly high variability across individual patients with similar amounts of hearing loss, QuickSIN SNR loss, or WRQ scores. For example, even in individuals with little to no hearing loss according to their HFPTA, the SSQ12-Speech5 values ranged from the lowest to the highest possible values (Fig. 1). Similar variability was observed with QuickSIN SNR losses (Fig. 2), or word recognition scores (Fig. 3). Thus, while average SSQ12-Speech5 scores readily track mean decrements in hearing or SIN abilities (Figs. 1, 2), the considerable variability in SSQ12-Speech5 scores for similar amounts of hearing or SNR loss greatly limits the predictive power of audiometric measurements. One implication of this variability is that clinicians and researchers should be extremely cautious about using mean data to assume a given SSQ12-Speech5 score for an individual patient. We speculate that some of this variance in SSQ12-Speech5 scores across individuals reflects the manner in which these tests were administered, while other sources of variance may reflect the limitations of such questionnaires. With regard to test administration, here the questionnaires were provided to the patient by front-desk staff with minimal instruction on how to complete them. Notably, test-retest reliability of the SSQ has been reported to be lower with self-administration than when administered by an interviewer (Singh & Kathleen Pichora-Fuller 2010). However, self-administration is unlikely to account for all of the variability here, as that same report also indicated that on average similar results were observed on the SSQ regardless of the procedure by which it was administered (Singh & Kathleen Pichora-Fuller 2010).

We think it more likely that the considerable between-patient variance on the SSQ12-Speech5 observed here reflects in part the limitations of questionnaires such as the SSQ12 or the SSQ itself. For example, there is growing awareness that questionnaires only partially reflect performance in real-world environments. Consistent with this idea, ecological momentary assessments (EMAs), in which perceived ratings of performance are measured in real time in real-world environments, have been shown to relate poorly to retrospective self-reports (akin to the SSQ) in a group of 39 older adults who used hearing aids (Wu et al. 2020). This discrepancy likely occurs because retrospective self-report questionnaires such as the SSQ are taken at a single point in time. Thus, they can be greatly influenced by memory, and the extent to which individuals weigh specific factors in their rating process (e.g., weighing difficulties in very challenging environments versus easier environments). In contrast, measures of EMA are less likely to be influenced by such factors, as they are obtained in natural environments during the course of the day. For these reasons, it has been suggested that EMA and traditional questionnaires may be capturing different aspects of the patient experience (Wu et al. 2020). With regard to the present data, if questionnaires such as the SSQ are providing limited information about the patient experience, then it seems plausible that variables such as hearing thresholds or SIN abilities would only be partially predictive of SSQ12-Speech5 scores. Similarly, self-report questionnaires such as the SSQ12-Speech5 may not capture differences between individuals with regard to the demands on their hearing in their daily life. For example, an individual who is retired and spends most of their day at home has very different demands on their hearing than does an individual who is working regularly with groups of people in challenging listening environments. Thus, similar amounts of hearing loss have the potential to limit activity or have other social consequences of perceived hearing difficulty and auditory disability (World Health Organization 2001). By this logic, some of the variance in SSQ12-Speech5 scores for individuals with similar hearing thresholds may reflect between-patient differences in the impact of their hearing loss on the ability to participate in their daily life. Last, one could argue that it is perhaps unrealistic to expect a ~10 dB change in hearing threshold, or a ~2 dB change in SNR loss, to relate in a linear fashion to a numerical rating scale of perceived difficulty. Hearing thresholds, QuickSIN SNR losses, and WRQ scores all have a certain amount of test-retest variance which can hinder observation of a linear relationship, let alone the test-retest reliability associated with questionnaire-based measures such as the SSQ12.

While audiometric thresholds or QuickSIN SNR losses only capture a portion of variance in SSQ12-Speech5 scores, they are relatively effective at predicting whether a given individual is likely to report a significant disability understanding speech-in-noise. Here, we used 6.83 as a cutoff for “good” versus “poor” SSQ12-Speech5 scores, as this value is 2 SDs from mean values observed in 103 young adults with normal hearing (Demeester et al. 2012). This value seems reasonable, given that others suggested a value of 6.6 as a cutoff for perceived auditory disability (Noble et al. 2012). Using the 6.83 cutoff value, both HFPTA and QuickSIN SNR loss were capable of identifying patients with perceived disability understanding speech-in-noise with a moderate degree of accuracy (AUC values ranging from 0.74 to 0.77). Specifically, individuals with moderate HFPTA values or moderate SNR losses on the QuickSIN had a high sensitivity for perceived disability as measured by the SSQ12-Speech5. Specificity, however, was only modest for predicting poor SSQ12-Speech5 scores. There are several implications to these results. First, they suggest that small differences in SSQ12-Speech5 scores across individuals may not be very meaningful when driving care, due to their high levels of variability and poor correspondence with objective audiometric data. However, if the goal is to predict whether an individual is likely to report difficulty understanding speech in challenging listening environments, then audiometric measures such as HFPTA or SNR loss appear to be reasonable choices. In contrast, WRQ scores do not appear to effectively predict perceived disability. Second, the poor specificity of these analyses appears to reflect the observation that many individuals with largely normal hearing, or normal speech-in-noise abilities, reported SSQ12-Speech5 scores suggesting difficulty understanding speech-in-noise. Figure 4 illustrates this relationship. Individuals who have SSQ12-Speech5 scores >6.83, and thus can be interpreted as reporting little difficulty understanding speech-in-noise, almost universally have HFPTA values <40 dB HL, and QuickSIN SNR losses <7 dB. For SSQ12-Speech5 scores <6.83, many individuals show the predicted result that these patients would likely have worse HFPTA and QuickSIN SNR losses. However, there are a number of these patients with low SSQ12-Speech5 scores who have either an HFPTA or QuickSIN SNR value that is either normal or consistent with a mild loss. We anticipate that there are several variables that may contribute to these lower SSQ12-Speech5 scores.

One possibility is that some individuals may be more prone to a "negativity bias" in which they weigh more heavily negative events in which they are having difficulty (Rozin & Royzman 2001). This could result in lower SSQ12-Speech5 scores despite having better-hearing thresholds or speech-understanding abilities in noise. On a closely related note, it is worth reiterating that the SSQ12-Speech5 ratings show very high between-subject variability, and we cannot rule out the possibility that some of the properties related to that extreme variability also contribute to some individuals having SSQ12-Speech5 scores <6.83 despite having normal HFPTA or QuickSIN values.

Another likely reason why some patients with normal HFPTA or QuickSIN SNR losses report significant difficulties understanding speech-in-noise is that these measures may not be fully sensitive to the deficits faced by some individuals. For example, individuals with a normal HFPTA may still have some degree of hearing loss, particularly above 4 kHz. Notably, reduced hearing in the ultra-high frequencies (thresholds 8 kHz or higher) has been related to worse speech-in-noise abilities (Hunter et al. 2020; Polspoel et al. 2022), and lower scores on the SSQ12 (Kamerer et al. 2022). On a closely related note,

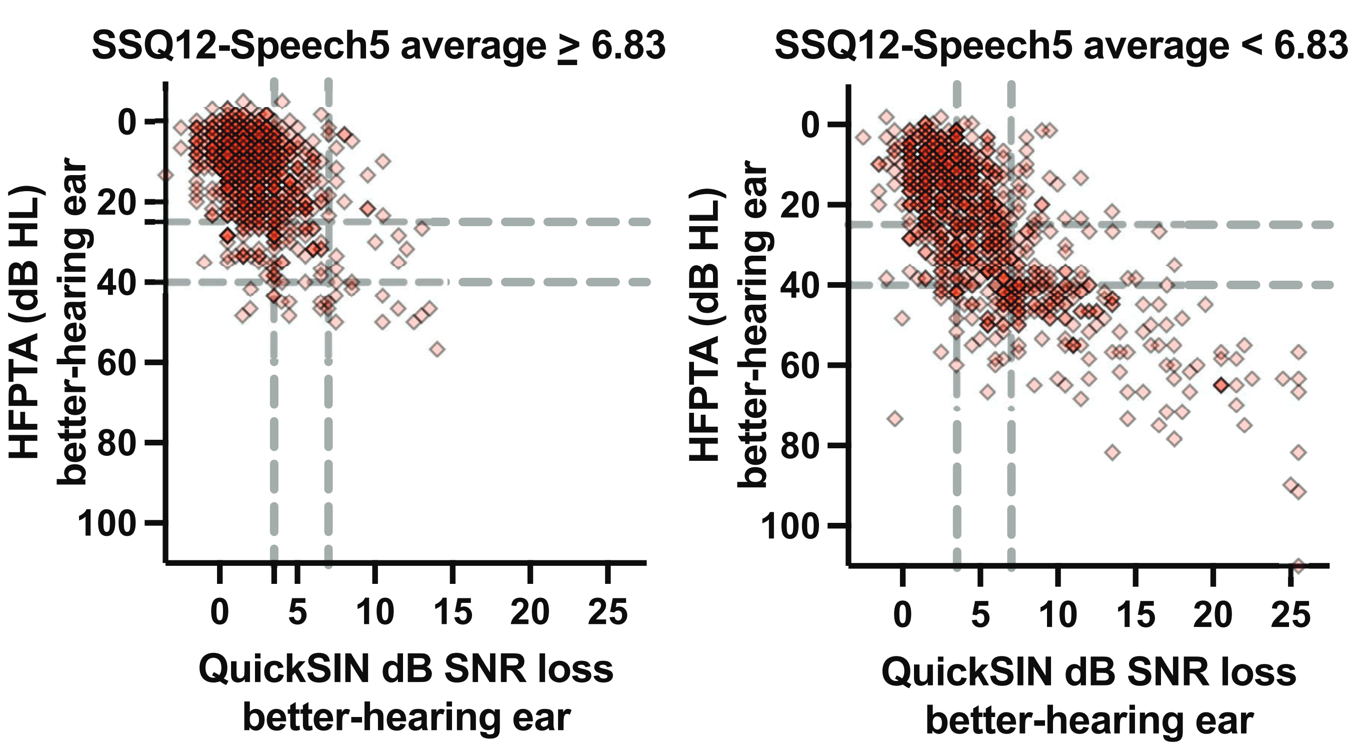

Fig. 4. This figure plots QuickSIN SNR losses (*x* axis) as a function of HFPTA (*y* axis). In both panels, each circle reflects an individual data point. To minimize the effects of overplotting, darker shading reflects values with more data points, while lighter shading reflects values with fewer data. The top dashed gray line reflects the boundary between normal hearing and a mild loss, while the bottom dashed gray line reflects the boundary between mild and moderate hearing loss. The left vertical dashed line denotes the boundary between normal and a mild SNR loss, and the right vertical dashed line denotes the boundary between mild and moderate SNR losses. The left panel displays data from patients with SSQ12-Speech5 scores ≥6.83, while the right panel includes patients with SSQ12-Speech5 scores <6.83. HFPTA indicates high-frequency pure-tone average; SNR, signal to noise ratio; SSQ12, Speech Spatial Questionnaire-12.

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individuals who have normal hearing, but have a history of noise exposure were also more likely to report lower SSQ12 values (Kamerer et al. 2022). Taken together, these data are consistent with the idea that a normal HFPTA may not indicate completely normal hearing, particularly above 8 kHz, and that hearing loss in those regions can be associated with poorer speech-in-noise abilities and SSQ12-Speech5 scores.

The QuickSIN also has properties that may in some instances make it less sensitive to the deficits faced by some individuals. For example, measures of cognitive function have been shown to influence performance on the QuickSIN (Nagaraj 2017; Humes 2021b), as well as the SSQ (Humes et al. 2013). More specifically, speech-recognition abilities in noise have been shown to be influenced by working memory capacity (Akeroyd 2008; Janse & Jesse 2014; Moore et al. 2014; Souza & Arehart 2015; Nagaraj 2017; Vermeire et al. 2019; Yeend et al. 2019) and cognitive flexibility (Helfer et al. 2020; Rosemann & Thiel 2020). Thus, one possibility is that individuals with strong top-down processing skills may perform better on the QuickSIN while still reporting difficulties understanding speech-in-noise via the SSQ12-Speech5. An alternate possibility is that the QuickSIN is not sensitive to other factors such cochlear synaptopathy (Kujawa & Liberman 2009, 2015), which has been suggested to be a mechanism by which individuals with largely normal hearing thresholds have difficulties understanding speech-in-noise. Consistent with this view, a recent review of SIN measures and suspected cochlear synaptopathy in humans suggested that SIN tests designed for clinical use such as the QuickSIN appear to be largely insensitive to cochlear synaptopathy (DiNino et al. 2022). Thus, to the extent to which cochlear synaptopathy contributed to perceived speech-in-noise deficits in this group of patients, individuals may have had normal HFPTA thresholds or QuickSIN SNR losses, but poor SSQ12-Speech5 values.

A third possible factor that may have influenced these results stems from the patient base from which these data were drawn. Here, all data were seen at a tertiary medical center in which many patients were seen in conjunction with an otologist or neurotologist. Thus, they were referred for assessment because of a perceived hearing problem, or other medical issue. This may have contributed to the lower SSQ12-Speech5 scores in some patients, as these patients are experiencing difficulty in at least some capacity enough to seek medical care. It is also worth noting that here we only reported data from patients with symmetric hearing thresholds. Previous research has demonstrated that SSQ values are lower in patients with asymmetric hearing thresholds (Noble & Gatehouse 2004; Moulin & Richard 2016), and that the thresholds in the better-hearing ear drive much of the variance in the SSQ in cases of asymmetric hearing (Moulin & Richard 2016). With regard to the present data, we expect that we would have observed slightly lower SSQ12-Speech5 scores if we had included patients with asymmetric hearing thresholds. However, we do not believe it would have changed our results appreciably given the smaller number of patients with asymmetric hearing thresholds (approximately 1/5 of the number as those with symmetric hearing).

CLINICAL IMPLICATIONS

One crucial aspect of the present data was that WRQ provided little to no information about perceived auditory disability as measured by the SSQ12-Speech5. This is particularly noteworthy given that WRQ has been the default test of speech perception in routine audiometric testing for over 70 years, and suggests that current standards of practice are insensitive to a primary concern of patients. In addition to providing no predictive value for SSQ12-Speech5 scores, WRQ scores were not predictive of which patients were likely to report SSQ12-Speech5 scores suggestive of greater perceived auditory disability. This likely occurred for several reasons. First and most important, decades of previous research have shown there is little relationship between perceived auditory disability speech understanding in quiet and perceived communication abilities in daily listening environments (Davis 1948; High et al. 1964; Giolas et al. 1979). Here, our work builds on this previous research and expands on it by illustrating that speech understanding in noise influences perceived auditory disability as measured by the SSQ12-Speech5. An alternative possibility is that the SSQ12-Speech5 is not sensitive to speech understanding abilities in quiet. Specifically, none of the questions that comprise the SSQ12-Speech5 subscale refer to speech understanding in quiet. Thus, it may be perhaps unsurprising that this measure did not predict performance on the SSQ12-Speech5. Last, the lack of variance in WRQ scores may have also contributed heavily to its inability to predict SSQ12 speech scores. Here, the vast majority of individuals had excellent WRQ scores ranging between 88 and 100%, which likely limited the predictive power of this variable.

In contrast with traditional measures of word recognition in quiet, the QuickSIN had some predictive power both for SSQ12-Speech5 scores, and perhaps more important, for identifying which patients were likely to report difficulties understanding speech in challenging environments according to the SSQ12-Speech5. This adds to a small but growing body of literature that suggests that speech-in-noise measures provide information not obtained by WRQ, and thus should be made a routine part of audiologic practice, as individuals can display difficulties understanding speech-in-noise despite having no difficulties understanding speech in quiet (Wilson 2011; Vermiglio et al. 2018; Fitzgerald et al. 2023). Measures of speech-in-noise have also been shown to more accurate at flagging the presence of a vestibular schwannoma than WRQ (Qian et al. 2023), and can even help predict which patients are likely to perform well in quiet (Fitzgerald et al. 2023). In contrast, WRQ has little to no predictive abilities for identifying patients with difficulties understanding speech-in-noise (Fitzgerald et al. 2023), and here we observed that it contributes little to no information about perceived auditory disability as reported by patients. Thus, these data are likely to be of interest for audiologists and physicians seeking to integrate measures of speech understanding in noise into routine clinical practice.

While the QuickSIN and the SSQ-Speech5 provide useful information about the measured or perceived SIN abilities, it is worth noting that none of these measures capture other aspects of functional impairment, such as activity limitation, participation restriction, or other social/emotional consequences of perceived hearing difficulty. These aspects are at the heart of the World Health Organization International Classification of Functioning, Disability and Health (World Health Organization 2001). These aspects of functional impairment are likely better captured by other questionnaires such as the Hearing Handicap Inventory for the Elderly (Weinstein & Ventry 1982; Weinstein 1986). Moreover, the importance of these variables has led some

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to argue that measures of perceived auditory disability should be a core part of determining which individuals have hearing difficulties, and may perhaps be more important than even pure-tone audiometry (Humes 2021a; Humes & Weinstein 2021). Ultimately, it is clear that different questionnaires focus on different aspects of perceived performance, as do different clinical measures of speech recognition in quiet and noise. Thus, care should be taken by clinicians in selecting which measures are utilized in clinical practice, as they appear to capture different components of the hearing experience of the patient.

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