AUDITORY INFORMATION PROCESSING AND FUNCTIONAL CORRELATES

by

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As members of the Audiology Doctoral Project Committee, we certify that we have read the project prepared by Brenden Bagnoli, titled Auditory Information Processing and Functional Correlates and recommend that it be accepted as fulfilling the Audiology Doctoral Project requirement for the Degree of Doctor of Audiology.

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ABSTRACT

Many adults report difficulty understanding speech in the presence of competing noise in spite of having normal audiometric thresholds. Possible factors contributing to this variability in perceived speech in noise (SPIN) performance are auditory mechanisms such as temporal processing and dichotic listening, as well as supramodal processes of attention and working memory. Clinically, behavioral tests are used to assess SPIN performance, but self-report questionnaires provide an alternative way to identify specific listening deficits. The goal of this study is to explore the variability observed among a number of different measures of auditory processing, the correspondence between the measures, and to identify underlying factors that contribute to overall speech-in-noise performance in a group of normal hearing individuals (n=20). A combination of behavioral tests and self-report questionnaires were administered. Principal Component analysis was used to examine the variability observed in the total set of measures and reduce the variability to a smaller set of factors. Factor analysis revealed six extracted components accounting for 81% of total variance that were determined to represent "Working Memory", "Temporal Processing", "Dichotic Listening", "Anxiety", "Self-Report Deficits", and possibly "Concentration". It was determined that working memory is a likely underlying factor affecting clinical speech in noise test performance in this sample of individuals. Additionally it was discovered that self-report questionnaires do not "co-load" onto components with behavioral measures, revealing that they are assessing different elements of auditory function and add value to test batteries.

BACKGROUND

One of the primary complaints of patients with hearing loss is difficulty understanding speech in the presence of competing signals or background noise (Smitts, Kramer, & Houtgast, 2006). Many studies have determined that audiometric thresholds do not always reflect the self-described hearing difficulty experienced by individuals (Gates, Cooper Jr, Kannel, & Miller, 1990; Jerger, Oliver, & Pirozzolo, 1990). Although speech-in-noise difficulties are expected when hearing loss is present, understanding speech in the presence of background noise can be difficult for individuals with normal hearing thresholds. In a survey of adults with normal audiometric thresholds, 12% identified themselves as having difficulty understanding speech in noise (Tremblay et al., 2015). Some groups of individuals are reported to be more prone to experiencing difficulty with speech in noise in the absence of a recorded hearing loss, such as individuals with autism spectrum disorder (Alcantara, Weisblatt, Moore, & Bolton, 2004; Carpenter, Estrem, Crowell, & Edrisinha, 2013) as well as individuals with central auditory processing disorder (Bamiou, Iliadou, Zanchetta, & Spyridakou, 2015) and those with more general listening difficulties due to attentional deficits (Moore, Ferguson, Halliday, & Riley 2007; Moore, 2012).

Often, individuals with functional listening difficulties are assessed to determine if their difficulties are due to an auditory processing disorder. According to ASHA 2005 guidelines for Central Auditory Processing Disorder (CAPD) assessment, a battery of tests should be administered that evaluates different levels of the auditory pathway (e.g., auditory nerve, brainstem nuclei, auditory cortex) and different aspects of auditory function such as stream segregation, binaural integration, temporal processing, and speech-in-noise perception. The inclusion of self-report indices and questionnaires in addition to these tests are also recommended as they can provide a more accurate depiction of listening difficulties experienced in real life and help guide clinicians in choosing appropriate diagnostic tests, interventions, and strategies to decrease the impact of such difficulties on the individual. Thus, the behavioral test results should be viewed as one part of a multifaceted evaluation, and should be included with other data regarding the individual's complaints and symptoms.

Traditional clinical measures of hearing sensitivity and listening function often do not reflect realistic listening experiences found in natural environments, and can in turn misrepresent difficulties perceived by the patient. Although important in assessing different levels of the auditory system and different aspects of auditory function, laboratory tests are administered in controlled, sound treated environments that minimize auditory and non-auditory variables that may not be controlled for in realistic listening environments (Bamiou et al., 2015). For example, clinical speech testing operates on the understanding that speech perception is measured by the ability to identify and repeat phrases without the need to comprehend it (Heinrich, Henshaw, & Ferguson, 2016). When these tests are performed in the presence of background noise, the noise often involves speechweighted noise or speech-like babble that is static and predictable. Although recent studies have simulated listening in a multi-source environment (e.g., Marrone, Mason, & Kidd Jr, 2008), these protocols may be too time intensive to be used efficiently in a clinic setting.

In spite of the lack of face validity between auditory tests performed under controlled situations and functional listening ability, a behavioral test battery administered in a clinical setting under earphones has value in that it is able to evaluate different levels of the auditory system that might explain an individual's difficulty with understanding speech in noise. The inclusion of self-report indices and questionnaires in addition to clinic-based tests can potentially provide a more accurate depiction of the listening difficulties an individual experiences in real life. However, questions that remain unanswered include: 1) Do self-reports of daily listening function reflect speech-in-noise test performance when administered in the clinical setting, and 2) What clinic-based auditory tests are most predictive of an individual's performance on speech-in-noise assessments?

Underlying Factors and Etiologies of Speech in Noise Processing Difficulties

Individuals with sensorineural hearing loss are expected to have difficulties hearing in noise because of reduced clarity and increased distortion of sound resulting from damaged outer hair cells, as well as damaged inner hair cells that are unable to complete the transduction mechanism to convert hydromechanical and acoustic information into neural signals. When hearing thresholds are in the normal range, SPIN difficulties may be a result of synaptopathy or "hidden hearing loss" (Schaette & McAlpine, 2011) which is thought to be due to degeneration of cochlear spiral ganglion neurons (Kujawa & Liberman, 2014) and typically attributed to noise induced excitotoxicity. Although synaptopathy has been documented in laboratory animals exposed to intense sounds, it is difficult to diagnose in a clinical setting. In this study, factors that are easily assessed in a clinical setting as contributing to or explaining speech-in-noise difficulties in individuals with normal hearing, are examined. The factors include:

1. Temporal Processing (an auditory process)
2. Attention and working memory (supramodal processes)
3. Hyperacusis (can impact cognitive processes)

Temporal processing. Good temporal processing skills, or the ability to process temporal aspects of sound over time, is an auditory process that is necessary for understanding speech in competing signals (Hopkins & Moore, 2009; Rawool, 2006). Deficits in temporal processing can lead to speech understanding difficulties due to inaccurate tracking of temporal cues or to an inability to use temporal “dips” or periods of low amplitude background noise to improve speech understanding (Alcantara et al., 2004).

Attention and Working Memory. Non-auditory supramodal processes such as attention and working memory can influence speech-in-noise processing abilities. The processing of auditory information within the central nervous system is complex and involves shared processing with higher order brain structures pertinent to language, attention, and executive control (American Academy of Audiology, 2010). In natural contexts, listeners are required to attend to and switch attention between signals to be able to maintain comprehension of the conversation. Working memory has increasingly become an important factor in explaining individual differences in an individual’s ability to process speech in noise (Ronnberg, Rudner, Lunner, & Zekveld, 2010; Rudner, Lunner, Behrens, Thoren, & Ronnberg, 2012).

Hyperacusis. A final factor that may contribute to speech-in-noise difficulties for some individuals is the presence of hyperacusis. Hyperacusis, or increased sensitivity to loud sounds in the presence of normal hearing sensitivity, has been linked to sound avoidance and greater levels of anxiety (Blaesing & Kroener-Herwig, 2012). This is particularly relevant to listening situations involving high levels of background noise which already require increased effort to understand one’s communication partners.

There is ample evidence that a number of factors contribute to “listening difficulties”. It is not surprising that ASHA 2005 guidelines for assessing central auditory processing disorder recommends that a test battery that examines a variety of auditory processes be used for assessment and that self-report indices and questionnaires also be used to assess the functional complaints of the client. It is not known if functional complaints correspond to test performance. Further, it is not known if the tests within the test battery measure a single underlying factor or if there is any degree of overlap. If tests used in a battery measure the same underlying processes, then the test battery may not be efficient or complete.

The goal of this study was to explore the variability observed among a number of different measures of auditory information processing, the correspondence between the measures, and to identify underlying factors that may contribute to speech-in-noise performance. Because of the exploratory nature of this study, a group of adults with normal hearing but no specific auditory complaints were recruited. A test battery was developed and administered to these subjects. The battery was developed to examine SPIN abilities, as difficulties with SPIN are the primary reason those with and without hearing loss seek evaluations and services from the Audiologist. The measures selected in this test battery included:

- Two laboratory based tests of SPIN abilities
- One self-rating of functional SPIN listening abilities
- One test of temporal processing
- One self-rating of anxiety
- One self-rating of hyperacusis (sensitivity to loud sounds)
- Assessment of attention skills
- Assessment of binaural integration/dichotic listening
- Assessments of auditory memory

Factor analysis was used to identify factors that account for the greatest amount of variance observed within this test battery. This approach can be helpful in determining the number and types of processes involved within this selected test battery.

METHODS

Participants

Twenty adults (3 males, 17 females) with normal hearing sensitivity were recruited using flyers (Appendix A) posted in the University of Arizona Speech, Language and Hearing Sciences department building. Pure tone audiometry was performed using a GSI AudioStar Pro audiometer with IP30 insert earphones for the purpose of obtaining audiometric thresholds to calculate a pure tone average, and to exclude any participants identified as having hearing loss (defined as having a threshold >20 dBHL for any frequency between 250 and 8000 Hz) from the study. All 20 participants were found to have normal hearing sensitivity.

Mean hearing thresholds for the 20 subjects, averaged across 0.5, 1, 2, 4 kHz, was 6.35 dB HL, SD = 4.2 dB HL. Participant ages ranged from 18 to 60 years (mean age of 26 years 4 months). History of head trauma or existence of a neurological diagnosis or learning disability were not considered to be exclusionary, however these details were documented for reference in a pre-experimental screening questionnaire (Appendix B). Minor head injuries were reported by three participants with an additional two participants reporting a diagnosis of mild concussion. One participant carries a diagnosis of Autism Spectrum Disorder. Of the twenty participants, 19 reported English as their native spoken language, with one participant reporting learning English as a second language at the age of 18 years. All recruited participants gave informed, signed consent. Ethics approval was obtained from The Institutional Review Board of the University of Arizona.

Tests Administered

Speech in Noise Performance

In the *Quick Speech-In-Noise test (QuickSIN)*, two 6-sentence lists designed to provide limited contextual cues were presented at a level of 70 dBHL via IP30 insert earphones. These sentences, spoken by a female talker, were presented simultaneously with a 4-talker babble designed to mimic realistic listening environments and social situations. The SNR was decreased, by increasing the presentation level of the multi-talker babble in 5 dB steps with each sentence spoken, beginning at +25 and eventually decreasing to 0 dB. Participants were asked to repeat the sentences presented, each of which contained five key words. A point was given for each correctly identified key word, and the total score was used to determine SNR Loss (25.5-total words correct). This SNR Loss score signifies the difference between the SNR required by the participant to achieve a 50% correct score and the SNR required by the average listener (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004).

The *Listening in Spatialized Noise Sentences (LISN-S)* test (Cameron, Glyde, & Dillon, 2011) was presented using test software downloaded onto a Dell Inspiron laptop with Sennheiser 215HD circumaural headphones connected to a Phonak branded buddy USB calibrated sound card that was then inserted into the headphone socket of the laptop. The test consists of 120 target sentences recorded by a single female speaker with a general American accent. For this test, the distractor stories consist of recordings by two female speakers with a clear standard American dialect, with the speaker changing depending on the selected listening condition. Target sentences and distractor stories were presented simultaneously in four different listening condition trials presented under circumaural headphones: (a) different voices presented at ±90°, (b) same voice presented at ±90°, (c) different voices presented at 0°, and (d) same voices presented at 0°. Participants were tasked with repeating words heard in each sentence, prompted by a 1000 Hz tone burst presented before each target sentence. Distractor stories were presented at a constant level of 55 dB SPL, while the target sentences are presented at an initial level of 62 dB SPL. The signal to noise ratio (SNR) was then adapted in each condition by either decreasing the target sentence presentation level by 2 dB if the listener repeated more than 50% of the words correctly, or by increasing the target sentence presentation level 2 dB if they scored less than 50%. Testing ceased in each condition if the participant either completed all 30 sentences, or if they had completed a minimum of 17 scored sentences with a standard error calculated to be less than 1 dB.

Functional Speech in Noise Questionnaire

The SSQ (Gatehouse & Noble, 2004) consists of 50 questions broken down into three subscales: *speech* (items 1-14), *spatial* (items 15-31), and *qualities* of hearing (items 32-50). The first section asks questions pertaining perceived abilities to understand speech in the presence of different distractors or in different environments, the second section referring to localization abilities, and the third and final section inquiring about sound segregation. Participants were asked to score themselves using a sliding scale with values ranging from 0 (complete inability) to 10 (greater ability). Scores for each subscale and for the entire SSQ were calculated as sums of the individual responses.

Auditory Temporal Processing

The *Gaps-in-Noise Test (GIN)* (Musiek et al, 2005) asks participants to identify 0-3 gaps of varying duration (0-20msec) inserted into a 5-sec burst of white noise presented at 50 dB SL re: participant’s PTA by pressing a button when each gap occurs. Performance was noted as a correct detection score (percent of gaps correctly identified) as well as a gap detection threshold. This threshold is defined as the shortest duration gap that can be identified correctly 50% of the time. A threshold of ≤6 msec and a detection score of ≥54% is considered normal.

Self-Ratings of Hyperacusis and Anxiety

The HYP (Khalfa et al, 2002) or Hyperacusis Questionnaire, comprises of 14 questions with three subscales assessing attentional, social, and emotional aspects of hyperacusis. Participants respond to each question with “Yes” (5 points), “Sometimes” (2 points), or “No” (0 points). The total was calculated by adding up the responses, with a score >28 indicating clinically significant hyperacusis.

The STAI, or State Trait Anxiety Inventory (Spielberger, 1970) contains two questionnaires; the state anxiety (A-State) scale asks 20 questions regarding how participants generally feel, while the trait anxiety (S-Trait) scale asks questions pertaining to how they feel at a particular moment. Questions were scored on a 4-point system ranging from 1 (Not at all) to 4 (Very much so).

Assessment of Attention Skills

The *Auditory Continuous Performance Test (ACPT)* (Riccio et al., 1996) has participants listen to a list of 96 monosyllabic words, and press a button when they hear the word “dog”. Performance was noted by the number of times the participant failed to identify the word “dog” (inattention errors) and the number of responses to words other than “dog” (impulsivity errors). These two scores were combined for a “total error” score.

Assessments of Memory

The *Clinical Evaluation for Language Fundamentals (CELF) Number Repetition* (Paslawski, 2005) is a measure of verbal working memory in which participants were tasked with repeating a string of spoken numbers. Sequences, presented free field, began with two spoken numbers and increased to a maximum of nine numbers. In the *Forward* condition, participants were tasked with repeating the sequence in the order that they heard, while the *Backward* condition required participants to repeat sequences in the reverse order of which they heard. Participants received one point for each sequence that was repeated in the correct order. Each trial consisted of two individual sequences of the same length, with participants advancing to the next trial after repeating at least one of the two sequences correctly.

Random Dichotic Digits (Strouse & Wilson, 1999) is a test in which participants are asked to recall digit pairs presented to both ears at 50 dB SL in any order. With each pair, a different digit is heard in each ear simultaneously. One, two, or three digit pairs may be presented within any one of the 54 trials, resulting in up to as many as 6 digits to be recalled. Scores were recorded as a percentage of correctly identified digits for each ear individually. The complexity of the task increases from easy (one pair) to difficult (three pair). The unpredictable change in task demand (e.g. for any trial the listener will be required to repeat the one, two, or three digit pairs) is also expected to increase the complexity of the listening task and greater demands on memory compared to a simple Dichotic Digit Task which assesses auditory binaural interaction processes (Musiek, Gollegly, Kibbe, & Verkest-Lenz, 1991).

Procedure

All testing was completed in a single-wall sound treated booth. With the exception of the LiSN-S and Forward/Background Digits Span test, all auditory tests were presented using a GSI

Audiostar Pro with insert earphones (RadioEar IP30). Behavioral tests and self-report questionnaires were administered to each participant in a single session with breaks permitted as requested by the participant. Questionnaires (Hyperacusis Questionnaire; State Trait Anxiety Index; Speech, Spatial, and Qualities Questionnaire) were completed prior to behavioral tests. Following the administration of the questionnaires, all remaining tests were administered according to a randomized list generated in Microsoft Excel.

Analyses

The IBM Statistical Package for the Social Sciences – SPSS program version 24 was used for descriptive and inferential statistical analyses. As an initial step before factor analysis, Pearson's correlations between the raw scores of the variables were determined. A varimax rotated factor analysis was completed to determine the number of factors accounting for variance amongst test results. Worse-ear scores were used for ear specific tests such as Gaps in Noise and Random Dichotic Digits. As there was extremely low variability between Gaps in Noise threshold measurements, the percent correct score was used for analysis. Percent correct scores for Random Dichotic Digits were calculated for the three following categories: double digits, triple digits, and total. All participants reached ceiling levels for Random Dichotic Digits single digits.

RESULTS

Correlations Between Behavioral Tests and Questionnaires

Averages of the performances from different participants were calculated for each test measure, as well as standard deviations for variance (Table 1). For the QuickSIN and ACPT test measures, a lower value indicates better performance. Table 2 shows Pearson's correlations between the 14 test variables. The Listening in Spatialized Noise Sentences (LiSN-S) sub scores (“talker advantage” and “speaker advantage”) correlated significantly with each other ($p < 0.01$) as well as with the QuickSIN test ($p < 0.01$ to < 0.05). The LiSN “Talker Advantage” also correlated significantly with the triple digit and total scores of the Random Dichotic Digits test, the SSQ “Quality” subscale, and State Trait Anxiety Index “S” scale ($p < 0.05$). A significant correlation was found between the LiSN “Speaker Advantage” and worse-ear Gaps in Noise scores ($p < 0.05$). QuickSIN test performance was also found to have a significant correlation with the State Trait Anxiety Index “S” scale ($p < 0.05$). All three SSQ subscales were found to correlate significantly with each other ($p < 0.01$ to < 0.05), while both the “Speech” and “Quality” subscales were found to correlate significantly with the Hyperacusis Questionnaire (p<

Table 1. Average Performance of Participants on Test Measures

	LiSN T (dB)	LiSN S (dB)	QuickSIN (dB SNR Loss)	Digit Span Total	ACPT Total Error	RDD Double Digits (%)	RDD Triple Digits (%)	RDD Total (%)	GIN (%)	HQ Total	STAIS Total	STAIA Total	SSQ "Speech" Total	SSQ "Spatial" Total	SSQ "Quality" Total
Average	10.01	12.25	.37	20.3	0.7	0.97	0.85	0.91	0.72	26.5	46.55	43.7	111.58	136.73	154.71
Standard Deviation	1.92	2.04	2.49	4.10	0.86	0.05	0.09	0.05	0.06	14.64	5.12	7.04	15.91	14.67	15.54

LiSN T, Listening in Spatialized Noise Talker Advantage; LiSN S, Listening in Spatialized Noise Spatial Advantage, QuickSIN, Quick Speech in Noise; ACPT, Auditory Continuous Performance Test; RDD, Random dichotic digits; GIN, Gaps in Noise; HQ, Hyperacusis Questionnaire; STAIS, State Trait Anxiety Index-S; STAIA, State Trait Anxiety Index-A; SSQ, Speech Spatial Qualities Questionnaire.

Table 2. Pearson's correlation between Auditory Tests, Supramodal tests, and Self-Report Questionnaires

	LiSN T	LiSN S	QuickSIN	Digit Span	ACPT	RDD Double	RDD Triple	RDD Total	GIN	HQ	STAIS	STAIA	SSQ Speech	SSQ Spatial	SSQ Quality
LiSN T	1														
LiSN S	**0.63****	1													
QuickSIN	**-0.70****	**-0.52***	1												
Digit Span	0.30	0.39	-0.40	1											
ACPT	0.09	-0.07	0.08	0.09	1										
RDD Double	0.19	-0.05	-0.22	0.23	0.16	1									
RDD Triple	**0.47***	0.22	-0.26	0.41	0.02	0.32	1								
RDD Total	**0.49***	0.19	-0.34	0.38	0.09	**0.59****	**0.94****	1							
GIN	0.23	**0.52***	-0.14	-0.06	-0.03	0.09	0.04	0.13	1						
HQ	-0.32	-0.13	0.19	-0.12	0.08	0.23	-0.17	-0.09	0.27	1					
STAIS	**0.45***	0.26	**-0.53***	0.16	0.42	0.35	-0.07	0.14	0.18	-0.05	1				
STAIA	-0.14	-0.11	0.03	-0.25	0.05	-0.05	0.08	0.07	-0.11	0.29	-0.04	1			
SSQ Speech	0.29	0.29	-0.23	-0.07	0.09	-0.039	0.05	0.05	0.03	**-0.51***	0.18	0.10	1		
SSQ Spatial	0.16	0.13	-0.33	0.10	0.18	0.15	0.19	0.25	0.11	0.13	0.43	0.19	**0.47***	1	
SSQ Quality	**0.55***	0.39	-0.36	0.15	-0.01	-0.05	0.39	0.36	0.28	**-0.49***	0.31	-0.33	**0.65****	**0.53***	1

*p < .05;
**p < .01 (2 tailed).
LiSN T, Listening in Spatialized Noise Talker Advantage; LiSN S, Listening in Spatialized Noise Spatial Advantage, QuickSIN, Quick Speech in Noise; ACPT, Auditory Continuous Performance Test; RDD, Random dichotic digits; GIN, Gaps in Noise; HQ, Hyperacusis Questionnaire; STAIS, State Trait Anxiety Index-S; STAIA, State Trait Anxiety Index-A; SSQ, Speech Spatial Qualities Questionnaire.

0.05). The forward/backward digit span and state trait anxiety index "A" scale did not show any significant correlations with any of the other tests used.

Factor Analysis

Principal components analysis revealed the presence of six factors with eigenvalues greater than Kaiser's criterion of 1 as seen in the scree plot (Figure 1). The first factor accounted for 29.41% of the variance, the second accounted for 14%, and the third accounted for 11.76% for a total of 55.2%. All six of the extracted factors combined accounted for 81% of the variance. The rotated factor loadings for the varimax rotated solution are shown in Table 3. A factor loading of >0.5 was considered to be appropriate when identifying variables loading onto each extracted component. As observed in Figure 2, each of the variables loads onto a single factor with the exception of the worse ear Random Dichotic Digits double digit scores, which loaded onto factors 2 and 4.

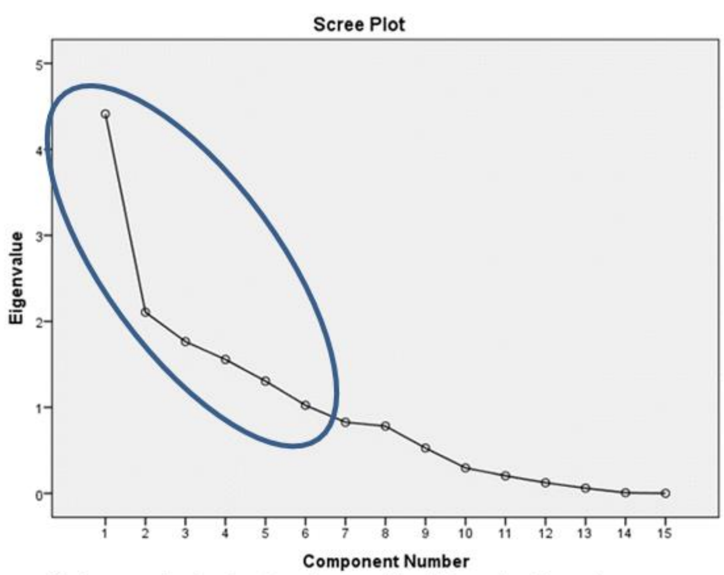

Fig 1. Scree plot, showing the variance explained (eigenvalues) by each component extracted by Principal Component analysis. The first six components combined were found to explain 81.13% of the total variance amongst test measures.

The tests that loaded onto factor 1 were both sub scores of the LiSN-S, the QuickSIN, and forward/backward digit span. Factor 2 was found to be heavily loaded onto by the Random Dichotic Digit scores. All three of the SSQ subscales as well as the Hyperacusis Questionnaire have high loading values with factor 3. Loadings that were found to be greater than 0.5 for factor 4 included the ACPT, Random Dichotic Digits double digit scores, and the state trait anxiety index “S” scale. Gaps in Noise was the only test loading highly with factor 5, while the state trait anxiety index “A” scale loaded by itself onto factor 6.

Table 3. Factor loadings of 6-factor solution using varimax rotation

	Factors (% variance explained)					
Variables	1 (29.4%)	2 (14.0%)	3 (11.8%)	4 (10.4%)	5 (8.7%)	6 (6.8%)
LiSN Talker	**0.736**	0.310	0.311	0.081	0.101	-0.119
LiSN Speaker	**0.755**	0.019	0.198	-0.163	0.422	-0.063
QuickSIN	**-0.865**	-0.132	-0.154	-0.139	0.003	-0.106
Digit Span	**0.564**	0.384	-0.17	0.089	-0.198	-0.255
ACPT	-0.090	0.033	0.042	**0.756**	-0.090	-0.033
RDD Double Digits	0.059	**0.582**	-0.231	**0.512**	0.109	-0.018
RDD Triple Digits	0.179	**0.932**	0.163	-0.137	-0.035	0.038
RDD Total	0.198	**0.956**	0.106	0.087	0.050	0.046
GIN	0.159	0.032	0.060	-0.015	**0.933**	-0.087
HQ	-0.209	-0.007	**-0.603**	0.217	0.494	0.408
STAIS	0.479	-0.085	0.163	**0.759**	0.101	0.017
STAIA	-0.060	0.030	-0.041	-0.048	-0.092	**0.941**
SSQ "Speech"	0.120	-0.063	**0.876**	0.078	-0.046	0.136
SSQ "Spatial"	0.090	0.165	**0.529**	0.434	0.191	0.405
SSQ "Quality"	0.237	0.237	**0.843**	0.046	0.204	-0.254

Factor loadings > 0.5 are bold
LiSN T, Listening in Spatialized Noise Talker Advantage; LiSN S, Listening in Spatialized Noise Spatial Advantage, QuickSIN, Quick Speech in Noise; ACPT, Auditory Continuous Performance Test; RDD, Random dichotic digits; GIN, Gaps in Noise; HQ, Hyperacusis Questionnaire; STAIS, State Trait Anxiety Index-S; STAIA, State Trait Anxiety Index-A; SSQ, Speech Spatial Qualities Questionnaire

DISCUSSION

This study sought to identify relationships between auditory tests, assessments of supramodal processes, and functional self-report questionnaires in an attempt to identify underlying factors that may explain the variability in speech in noise perception abilities of adults with normal pure-tone audiograms.

Self-reports of Listening Function and SPIN Test Performance. The only statistically significant correlation observed between the questionnaires and auditory tests was between the

LiSN Talker advantage and the “Quality” subscale of the SSQ, as well as the state trait anxiety index “S” scale. This relationship could possibly be expected, as the “Quality” subscale of the SSQ asks questions directly related to the ability to distinguish different speakers by the sound of their voice, and the LiSN Talker advantage refers to the benefit received by the listener when the target sentences and background noise are spoken by two different women compared to their performance when both are spoken by the same woman. It is interesting then, that these different tests were not observed to load onto the same component extracted by factor analysis. One thing to consider is that linear regressions are simple tests that only look at two variables, whereas the factor analysis considers all variables present and how a relationship between two tests could be influenced by others.

Speech-in-Noise Performance and Underlying Mechanisms. A statistically significant correlation found to be of interest was between the LiSN Speaker advantage and worse ear Gaps in Noise performance. While both tests do investigate auditory mechanisms with temporal elements, the LiSN Speaker advantage is a representation of masking level difference at the level of the brainstem that relies on binaural timing cues, whereas the Gaps in Noise test assesses finer temporal processing abilities related to how quickly and accurately auditory nerve fibers are able to respond to the onset and offset of a broadband noise signal. It should be noted however, that while these two tests appear to correlate significantly, a linear regression model revealed that a low percentage of the variation could be explained by the relationship.

Correlations are limited in that they can only offer information regarding the relationship between two test measures. By completing a factor analysis, the entire test battery can be evaluated on a broader level. The factor analysis identifies factors that account for the greatest amount of variance observed within the test battery, and offers insight on the number and types of processes involved within the test battery. This can help determine when to eliminate tests that are redundant and do not offer additional information, and confirm that particular tests are evaluating a single process. Figure 2 shows a visual representation of the 6 factors or components that were extracted and identified as explaining 81% of the total variance amongst the 15 test measures, as well as the test measures that loaded highly onto each component. The percentages within each circle is how much of the total variance is explained by that particular factor, and the values above each arrow represent the loading factor of that particular test measure.

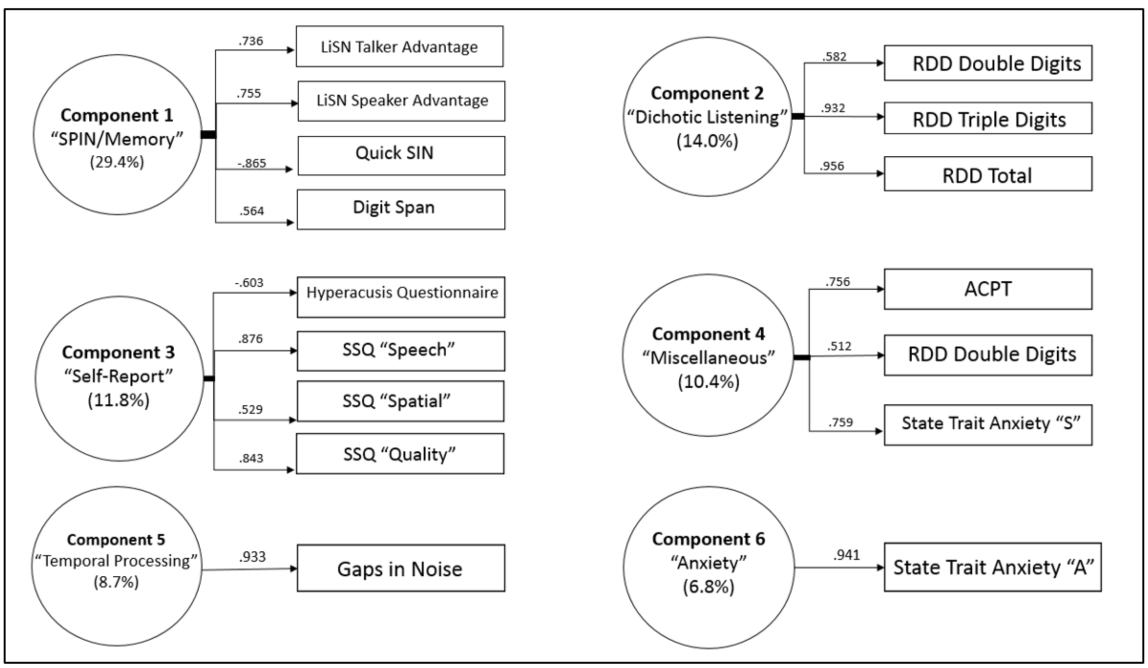

Fig. 2 Visual representation of factor loadings of 6-factor solution

Component 1, identified as the "Speech in Noise & Memory" component, was loaded highly onto by all of the present speech in noise performance tests as well as the forward/backward digit span test. This connection may reveal that working memory is a vital underlying factor of speech in noise perception abilities, and may help explain the variability in performance amongst adults with normal hearing sensitivity. Additionally, while the LiSN was thought to be measuring very different aspects of speech in noise performance than the QuickSIN, it loaded onto the same component with a similar loading value. This could suggest that, in normal hearing individuals, these two tests are not able to measure different aspects of information. Administering both of these tests in the same test battery could be considered redundant and inefficient with this line of thinking.

Components 2 & 5. Two of the extracted components were found to load onto a single auditory test, with "Dichotic Listening" component 2 loading entirely onto worse-ear Random Dichotic Digit scores (double digit, triple digit, and total) and "Temporal Processing" component 5 loading primarily onto worse-ear Gaps in Noise performance. One way to interpret this could be that these are "pure" measures that are able to isolate and assess a single aspect of auditory information processing without being affected by other identified components. It was initially anticipated that Random Dichotic Digit performance would load onto component 1 as a result of the increased complexity and memory load. Instead, the factor loading values would suggest that it is essentially assessing one element of information, which is likely pertaining to dichotic listening abilities.

Component 3. All three of the SSQ subscales as well as the Hyperacusis Questionnaire were found to load heavily onto component 3, labeled as the "Self-Report" factor, as well as show significant correlations amongst each other. The factor loading observed could possibly indicate that these questionnaires are able to identify or evaluate aspects or deficits in listening abilities that are not reflected by the other behavioral test measures. If this is the case, this would support the suggestion made by Bamiou et al. (2015) to implement questionnaires in addition to behavioral tests to help identify and quantify specific symptoms in real life to then guide intervention strategies.

Component 4 was designated as the “miscellaneous” factor, as there are no apparent links between the test measures that loaded onto it. One interesting piece of information that could link the ACPT and Random Dichotic Digits Double Digit performance is that nearly all participants performed at ceiling levels, significantly reducing the variability of those test measures amongst participants. It could be posited that there is a “Concentration” component as the State Trait Anxiety Index “S” investigates feelings related to anxiety at the time of completion, and is loading onto the same factor as the ACPT which measures impulsivity and requires participants to react quickly and accurately. This would not explain why Random Dichotic Digit performance for double digits loaded onto Component 4 and not any of the other Random Dichotic Digit scores, however it should be noted that the loading factor is only .512 compared to the loading factors of .756 and .759 of the ACPT and State Trait Anxiety Index.

Component 6 could be labeled as the “anxiety” factor, as the only test measure to load upon it was the State Trait Anxiety Index “A”, which asks questions pertaining to how an individual feels or experiences symptoms related to anxiety on a general basis, as opposed to the State Trait Anxiety Index “S”, which investigates how the individual is feeling at the time of completing the questionnaire which occurred immediately prior to completion of the test battery.

Conclusions

The goal of this study was to explore the variability observed among a number of different measures of auditory processing, the correspondence between the measures, and to identify underlying factors that contribute to speech-in-noise performance. In trying to identify these factors, the following conclusions were uncovered:

- Working memory is likely an underlying factor contributing to clinical speech in noise test performance
- Administering multiple Speech in Noise tests (such as the QuickSIN and LiSN-S) may be redundant when assessing individuals with normal hearing
- Two behavioral tests, the Gaps in Noise and Random Dichotic Digits test, were identified as being the sole test variable to load onto their respective components, suggesting that they are "pure" test measures and have added value in a test battery as they are able to isolate a single aspect of auditory processing
- Self-Report Questionnaires (such as the HQ and SSQ) do not "co-load" onto components with behavioral test measures, and are likely assessing very different elements of auditory function and should be included in test batteries designed to identify listening deficits.

Limitations and Future Directions

This study was intended to be a preliminary study, and was not designed to target individuals with reported listening difficulties, but rather a wide range of young adults with normal hearing sensitivity. The correlations and factors identified are likely to be highly influenced by the population that is being assessed. Thus, it is recommended that these analyses be completed with different populations (e.g., individuals with Autism Spectrum Disorder, Traumatic Brain Injury, documented auditory processing disorder) to determine test batteries that may be most appropriate for those individuals. It should also be kept in mind that a relatively small sample side (n=20) was used in this study, limiting the amount of variability that could occur and possibly resulting in larger standard errors.

APPENDIX A – RECRUITMENT FLYER

Adults with normal hearing are needed for a study examining Speech in Noise Processing at the U of A!

We are recruiting adults, age **18 years to 60 years.**

Participation involves filling out questionnaires, and participating in tasks in which you repeat words or numbers.

Principal Investigators: David Velenovsky, Ph.D. & Linda Norrix, Ph.D.

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An Institutional Review Board responsible for human subjects research at The University of Arizona reviewed this research project and found it to be acceptable, according to applicable state and federal regulations and University policies designed to protect the rights and welfare of participants in research.

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APPENDIX B – SCREENING QUESTIONNAIRE

Participant #: ___________ **Age:** _________ **Sex:** ___________ **Date:** ____________

Do you have a known hearing loss? Yes __________ No ___________

Do you have a diagnosis of Autism Spectrum Disorder? Yes __________ No ___________

If yes, when did you receive your diagnosis?

Have you had chronic ear infections? Yes __________ No ___________

If yes: Have you had Pressure Equalization tubes placed? Yes __________ No ___________

Have you experienced any head injuries or concussions? Yes __________ No ___________

If yes, please explain below (extent of injury and # of occurrences).

Have you been diagnosed with a learning disability? Yes __________ No ___________

If yes, please explain below.

Have you been diagnosed with a neurological condition? Yes __________ No ___________

If yes, please explain below.

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