ASHA American Speech-Language-Hearing Association

AJA

Research Article

Relationship Between Cognitive Abilities and Basic Auditory Processing in Young Adults

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ARTICLE INFO

Article History:
Received December 4, 2023
Revision received January 25, 2024
Accepted January 29, 2024

Editor-in-Chief: Erin M. Picou
Editor: Christina Roup

https://doi.org/10.1044/2024_AJA-23-00261

ABSTRACT

Purpose: The diagnosis of auditory processing disorder (APD) is controversial particularly due to the influence of higher order factors of language and cognition on the diagnostic APD testing. As a result, there might be a need for testing for other domains (e.g., cognition) along with conducting the diagnostic APD testing to rule out the influence of other domains. In order to make recommendations on whether cognitive testing is needed along with the auditory processing testing, as a starting point, the current study was conducted to examine the relationship between cognitive abilities and basic auditory processing in young adults.

Method: A total of 38 young adults with normal audiometric thresholds between 250 and 8000 Hz participated in this study. They were tested on their executive function, language, processing speed, working memory, and episodic memory components of cognitive testing and tests for temporal fine structure and spectrotemporal sensitivity for auditory processing testing.

Results: No significant correlation was found between the cognitive tests and the tests for basic auditory processing in young adults.

Conclusions: These findings present contrast to the existing findings in children and older adults where a stronger correlation between cognitive abilities and auditory processing has been found. The current findings suggest that testing for cognitive abilities may not be needed when testing for basic auditory processing in young adults.

Auditory Processing Disorder (APD), Central Auditory Processing Disorder, or (Central) Auditory Processing Disorder, is one of the most intriguing and controversial topics in the field of audiology. Some aspects that make APD problematic, both in theory and in clinical practice, include comorbidity with other disorders (e.g., dyslexia), lack of gold standard (Moore, 2018; Vermiglio, 2018), and influence of higher order factors of language and cognition on the diagnostic testing of APD (Cacace & McFarland, 2008, 2013; Dillon & Cameron, 2021). In order to make recommendations on whether testing of higher order factors (e.g., cognition) should accompany testing for auditory processing, investigations should be conducted to study the extent of relationship between these higher order factors and auditory processing. As a starting point in the direction, the current study was conducted to examine the relationship between cognitive abilities and basic auditory processing in young adults.

According to the American Speech-Language-Hearing Association (ASHA, 2005a, Definition and Nature of APD, Paragraph 1), APD is defined as a deficit in one or more of the following auditory processes: temporal processing including temporal integration, temporal ordering, and temporal masking; auditory discrimination and auditory processing in adverse listening conditions; and binaural auditory processing including sound localization and lateralization, and dichotic listening. According to the American Academy of Audiology (AAA, 2010), APD can be defined as "difficulties in the perceptual processing of auditory information in the central nervous system and the

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Disclosure: *The authors have declared that no competing financial or nonfinancial interests existed at the time of publication.*

neurobiological activity that underlies processing." Furthermore, ASHA (2005b) suggests that APD is limited to deficits in the processing of information in the auditory nervous system and is not a result of higher order factors such as language/cognition. Some examples of behavioral tests that are suggested for APD testing include Dichotic Digit/Consonant–Vowel test, Pitch/Duration Pattern test, Gap Detection test, and Speech-in-Noise test (ASHA, 2005a). An APD diagnosis can be given if scores less than 2 or 3 *SD*s on the behavioral testing is achieved (AAA, 2010; ASHA, 2005b). One of the central points of controversy around APD since the past several decades has been whether APD is and/or should be specific to the auditory domain. According to some reports, the distinctiveness of APD as a disorder can be confirmed only if APD can be shown to be specific to the auditory domain (Cacace & McFarland, 2008, 2013; Jerger & Musiek, 2000). On the other hand, there are reports that suggest that it may not be accurate to consider APD as a domain-specific disorder, mainly due to the inability to separate auditory processing from cognition (Dillon et al., 2014; Moore & Ferguson, 2014). In addition, the position statement by the British Society of Audiology (2018) reflects that APD may consist of aspects related to speech, language, reading, memory, and executive function. To summarize, APD as a concept has been controversial as there is no consensus across our national and international societies on whether higher order factors of language and cognition should be considered within the definition of APD. This position is further complicated by the existing test battery of APD that is influenced by the aforementioned factors.

APD has been found to exhibit comorbidity with other disorders such as dyslexia, developmental language disorder (DLD), and attention-deficit/hyperactivity disorder (Dawes & Bishop, 2009, 2010; de Wit et al., 2016, 2018; Miller & Wagstaff, 2011; Sharma et al., 2009). Those diagnosed with APD and those diagnosed with dyslexia have been found to perform similarly on the tasks related to auditory processing, IQ, language, and literacy. As a result, there is significant overlap (almost 50%) between those diagnosed with APD and those with dyslexia or DLD (Dawes & Bishop, 2010). Furthermore, it has also been found that those diagnosed with APD also perform poorly on the tasks related to language and communication, and attention and memory (de Wit et al., 2016), and there were minimal differences between those diagnosed with APD and those affected with developmental disorders. It is to be noted that the issues related to comorbidity of APD with other disorders, and lack of specificity of APD to the auditory domain, might stem from the fact that the current behavioral APD test batteries, based on the characteristics of APD defined by ASHA (2005a) and AAA (2010), are affected by domains outside audition. For example, speech-in-noise testing can be influenced by linguistic abilities, duration and pitch pattern tests can be influenced by differences in memory, and all behavioral APD tests require attention of the participant. Thus, it is possible that the effects of lack of domain specificity and comorbidity are potentially stemming from the confounding effect of the constituents of the tests.

Previous research has found significant correlation between auditory processing and cognitive testing. Studies have found a correlation between working memory and auditory processing (Keller et al., 2006; Riccio et al., 2005; Sharma et al., 2009; Wilson et al., 2011). There are also studies that have found significant correlation of auditory processing with attention (Moore et al., 2010; Sharma et al., 2009) and nonverbal IQ (Ferguson et al., 2011; Gyldenkærne et al., 2014) components of cognitive testing. However, it is to be noted that these studies included the auditory processing tests that involved higher order factors of language and cognition. For example, tests such as frequency pattern and dichotic digits heavily involve working memory, whereas staggered spondaic word test involves language component.

In order to circumvent the effects of the confounding higher order factors (e.g., language, working memory, etc.), there have been suggestions regarding the use of test batteries that investigate the lower level or basic auditory processing, which is relatively independent of the extraneous factors of language and cognition (Maggu & Overath, 2021). On the other hand, there are also suggestions on the use of multidomain testing approach for APD where other domains are also tested along with the auditory domain. For example, conducting language testing along with APD testing to rule out the influence of language and thus ascertaining that the observed effect is from the auditory domain. In any case, understanding the effect of these higher order factors on auditory processing is vital. Furthermore, it is even more vital to study the effects of these higher order factors (e.g., cognition) on auditory processing after controlling the confounding effects of these higher order factors from these tests, that is, to test the relationship between cognitive abilities and low-level auditory processing. Recently, one such test battery known as the Portable Auditory Rapid Testing (PART) battery has been developed by the University of California Brain Game Center (Gallun et al., 2018). PART battery contains subtests that aimed at evaluating tone perception in noise, gap detection, temporal modulation (TM), spectral modulation (SM), spectrotemporal modulation (STM), and competing sentence perception. PART battery is free-downloadable and can be run via an iPad. PART battery has been validated on young normal-hearing individuals with a decent test–retest reliability across sessions

(Lelo de Larrea-Mancera et al., 2020), and across sites (Gallun et al., 2018) along with reliability of administration of the battery on participant-owned devices (Lelo de Larrea-Mancera et al., 2022) further adding to its versatility to conduct remote assessments. As a result, PART battery has started to find its usage in testing of clinical population (Diedesch et al., 2021). Diedesch et al. (2021) conducted a study with nine young normal-hearing subjects (M_{age} = 21.3 years) and seven older hearing-impaired subjects (M_{age} = 64.9 years) where they found an overall significant correlation of pure-tone average of 500, 1000, 2000, and 4000 Hz with the PART battery measures. Subtests of PART battery have been used to study their relationship with cognitive abilities (Charney & Srinivasan, 2020). Charney and Srinivasan (2020) compared 15 young adults (M_{age} = 25.25 years) with 25 older adults (M_{age} = 64.04 years) on their working memory and spatial release of masking component of PART battery and they found that there was difference between the two groups on both spatial release and cognitive abilities. Furthermore, they also found a significant correlation between spatial release of masking and cognitive abilities. However, it was unclear whether the correlation in their study was driven by one or both the groups. In the current study, we are interested in examining the temporal fine structure (TFS) and spectrotemporal sensitivity (STS) components of the PART battery. TFS components were selected because TFS tests have been found to examine the timing of auditory nerve fibers, which has been found to correlate with speech perception in noise (Füllgrabe et al., 2015). More specifically, TFS has been found to be affected in cases of auditory neural degeneration (e.g., in aging, Füllgrabe et al., 2015). Similarly, gap detection has been found to be affected in individuals with APDs, especially temporal processing deficits (Dias et al., 2012; Phillips et al., 2010). Those with binaural processing deficits may show discrepancies across the diotic versus dichotic frequency modulation tasks (Diedesch et al., 2021). STS components including SM, TM, and STM were used in order to employ complex signals that share similarities with speech signals, in terms of frequency and TMs, to challenge the central auditory system but without tapping into the linguistic resources (e.g., speech processing) in the brain (Diedesch et al., 2021).

To summarize, in the current study, we aimed at understanding the extent to which cognitive abilities influence basic auditory processing in young adults with normal hearing. For testing auditory processing, we used the PART battery developed by the University of California Brain Game Center (Gallun et al., 2018). More specifically, we used tests for TFS and STS. For evaluating cognitive abilities, we used the cognition battery of the National Institutes of Health Toolbox (Weintraub et al., 2014). The cognition battery consisted of tests focusing on executive function, memory (episodic and working), language, and processing speed. We conducted separate Pearson correlation tests to understand the extent of relationship between cognitive abilities and basic auditory processing. Depending on the correlation results between the cognitive abilities and basic auditory processing, we aimed at making recommendations on whether testing for cognitive abilities is needed during testing for basic auditory processing and, if yes, for which specific basic auditory processing tests.

Method

Participants

A total of 48 young adults were recruited via posting flyers or via the SONA Systems (n.d.) of Hofstra University. They were either paid at the rate of $10/hr or were granted course credits for their participation in the study. This study was approved by the institutional review board of Hofstra University (HUIRB Approval Ref#: 20220826-SLH-HPHS-MAG-1). To participate in the study, subjects signed a written, informed consent form. There was no time limit for them to read and sign the consent form. Their questions, if any, were answered. After excluding 10 outlier subjects, who were unable to complete the auditory processing tasks and/or cognitive tasks due to time-constraint or technical difficulties, we went ahead with analyzing the available data from 38 subjects (11 men and 27 women; M_{age} = 19.28 years). For completing the following method subsections, a total of 100 min were needed by each subject. All testing was conducted by student research assistants who were trained by the principal investigator (first author).

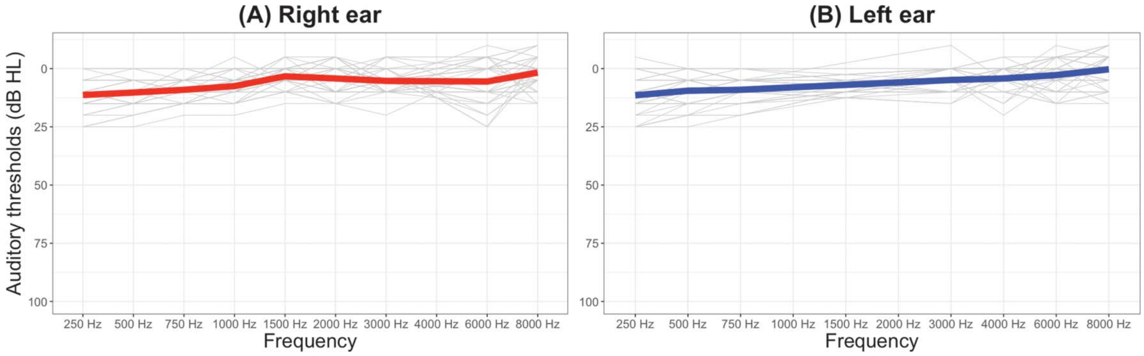
Hearing Testing

All participants were evaluated for their air-conduction hearing abilities between 250 and 8000 Hz via a GSI-18 audiometer (Grason-Stadler Inc.) using pure tones routed via TDH-39 supra-aural headphones, in a quiet acoustically padded room. All participants were required to have pure-tone thresholds of ≤ 25 dB HL between 250 and 8000 Hz. Figure 1 depicts the hearing thresholds for all participants for their right (see Figure 1A) and left (see Figure 1B) ears.

Cognitive Testing

In order to test the cognitive domains of executive function and attention, episodic memory, language, working memory, and processing speed, cognitive testing was conducted using the National Institutes of Health (NIH)

Figure 1. Audiograms depicting the thresholds of the 38 subjects for the (A) right ear and (B) left ear. Red and blue lines correspond to the mean thresholds for the right ear and left ear, respectively.



Toolbox Cognition Battery (Weintraub et al., 2013, 2014) via an iPad (9th Gen, Version 15.4.1). In order to test executive function and attention, the Dimensional Change Card Sort (Zelazo, 2006), which evaluates the ability to switch conceptual frameworks, and Flanker task (Eriksen & Eriksen, 1974), which evaluates inhibitory control and selective control, were used. For testing episodic memory, Picture Sequence Memory subtest that contained nonverbal picture stimuli was used. For testing language, Picture Vocabulary Test was used. For testing working memory, the List Sorting Working Memory Test was used. For testing processing speed, Pattern Comparison Processing Speed Test was used. Table 1 summarizes the different cognitive domains that were tested by different tests within the NIH cognition battery.

Auditory Processing Testing

For evaluating basic auditory processing, we used subsections from the PART battery (Gallun et al., 2018). PART was downloaded on an iPad (9th Gen, Version 15.4.1) via the App Store. We used the subtests of PART that addressed the TFS and STS. For evaluating TFS, we used gap detection, diotic frequency modulation, and dichotic frequency modulation subtests. For evaluating STS, we used TM, SM, and STM tasks of the PART battery (see Diedesch et al., 2021; Lelo de Larrea-Mancera et al., 2020).

Table 1. Summary of the tests that were used from the National Institutes of Health (NIH) Toolbox Cognition Battery and the corresponding cognitive domains tested.

NIH Toolbox Cognition Battery tests	Cognitive domain tested
• Dimensional Change Card Sort Test • Flanker Inhibitory Control and Attention Test	Executive function
Picture Vocabulary Test	Language
Pattern Comparison Processing Speed Test	Processing speed
List Sorting Working Memory Test	Working memory
Picture Sequence Memory Test	Episodic memory

TFS Tasks

Gap detection test (Gallun et al., 2014; Hoover et al., 2019) included the subjects to identify the pair of tonebursts that had a gap between them as compared to that pair that was played sequentially and did not have a gap between them. Smallest perceived gap was ascertained via the staircase method starting at the initial value of 20 ms. Stimuli consisted of 4-ms 500 Hz tonebursts that were presented diotically.

Diotic Frequency Modulation (FM; Grose & Mamo, 2012; Hoover et al., 2019; Whiteford et al., 2017; Whiteford & Oxenham, 2015) consisted of comparing 2 Hz modulation rate to standards with carrier frequency between 460 and 550 Hz. Smallest perceived modulation detection was obtained via the staircase method starting at an initial value of 6 Hz in a diotic manner.

Dichotic FM (Grose & Mamo, 2012; Hoover et al., 2019) consisted of stimuli that were similar to the diotic FM task with the exception that the target 2 Hz modulation rate is presented in an antiphasic manner between the ears. Smallest perceived modulation detection was obtained via the staircase method starting at an initial value of 3 Hz in a dichotic manner.

Spectrotemporal Sensitivity Tasks

Stimulus used for these tasks is 400–8000 Hz broadband noise that could be unmodulated, spectrally modulated, temporally modulated, or spectrotemporally modulated.

TM (Viemeister, 1979) entailed comparison of 4 Hz temporal amplitude modulation to the unmodulated standard stimulus. Smallest perceived modulation depth (in dB) was obtained.

SM (Hoover et al., 2018) entailed comparison of 2 cycles per octave to the unmodulated standard. Smallest perceived modulation depth (in dB) was obtained.

STM (Bernstein et al., 2013; Mehraei et al., 2014) contained stimuli similar to the TM and SM tasks and entailed comparing the 2 cycles per octave and 4 Hz amplitude modulation to the unmodulated standards. Smallest perceived modulation depth (in dB) was obtained.

Planned Statistical Analysis

In order to understand the relationship between each of the tests of the basic auditory processing test battery with each of the tests of the cognitive test battery, a total of 36 Pearson correlations were conducted. To overcoming the risk of increasing the Type I error, that is, erroneously detecting an effect in the absence of any true effect, Bonferroni correction was applied to obtain an adjusted target *p* value (Curtin & Schulz, 1998). In this case, the adjusted target *p* value came out to be .0014 (i.e., 0.05/36).

Results

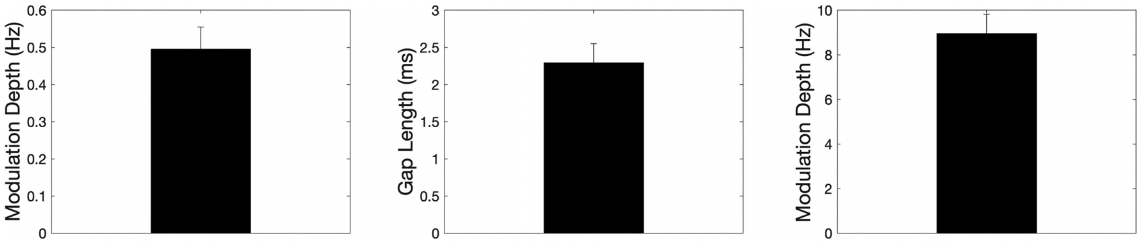
Descriptive data analysis (see Figure 2) revealed that the results from Dichotic FM (M = 0.49, SD = 0.06), Gap Detection (M = 2.29, SD = 1.59), Diotic FM (M = 8.95, SD = 5.35), SM (M = 1.83, SD = 0.11), TM (M = 1.93, SD = 0.69), and STM (M = 1.55, SD = 1.28) were similar to those found in the previous studies that have used the PART battery or similar tests (Gallun et al., 2014, 2018; Grose & Mamo, 2012; Hoover et al., 2015, 2019; Viemeister, 1979).

In order to examine the relationship between cognitive abilities and basic auditory processing abilities, a total of 36 correlations were conducted. For a correlation to be significant, the *p* value needed was < .0014 after correcting for multiple comparisons using Bonferroni correction (i.e., 0.05/36).

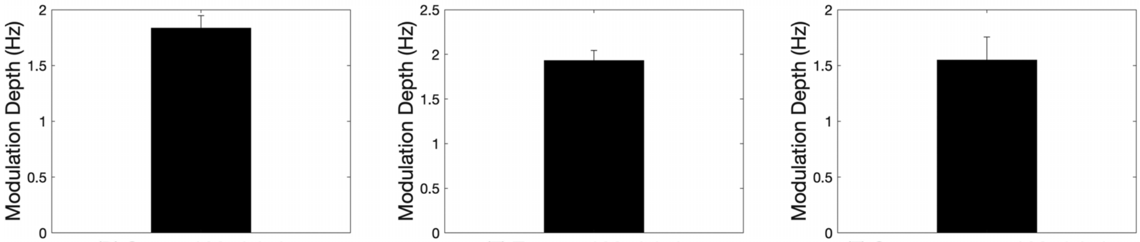
Relationship Between Cognitive Abilities and TFS Perception

Overall, it was found that there was no significant correlation between the tests for cognitive abilities and tests for TFS auditory processing (see Figure 3 and Table 2). More specifically, Gap Detection did not show any significant correlation with Picture Vocabulary (R = −.02, p = .902), Flanker (R = −.01, p = .947), Sorting Working Memory (R = −.1, p = .554), Dimensional Change Card Sort (R = −.13, p = .424), Pattern Comparison (R = −.16, p = .345), and Picture Sequence memory (R = −.14, p = .405). Dichotic FM did not show any significant correlation with Picture Vocabulary (R = .05, p = .755), Flanker (R = .19, p = .25), Sorting Working Memory (R = −.02, p = .892), Dimensional Change Card Sort (R = .12, p = .49), Pattern Comparison (R = −.09, p = .592), and Picture Sequence memory (R = .02, p = .894). Similarly, Diotic FM did not show any significant correlation with Picture Vocabulary (R = .03, p = .877), Flanker (R = −.31, p = .059), Sorting Working Memory (R = −.25, p = .128), Dimensional Change Card Sort (R = .1, p = .545), Pattern Comparison (R = −.13, p = .449), and Picture Sequence Memory (R = −.18, p = .283).

Figure 2. Bar plots describing the mean performance of the subjects on (A) Dichotic FM, (B) Gap detection, (C) Diotic FM, (D) Spectral Modulation, (E) Temporal Modulation, and (F) Spectrotemporal Modulation. Error bars indicate +1 *SEM*.

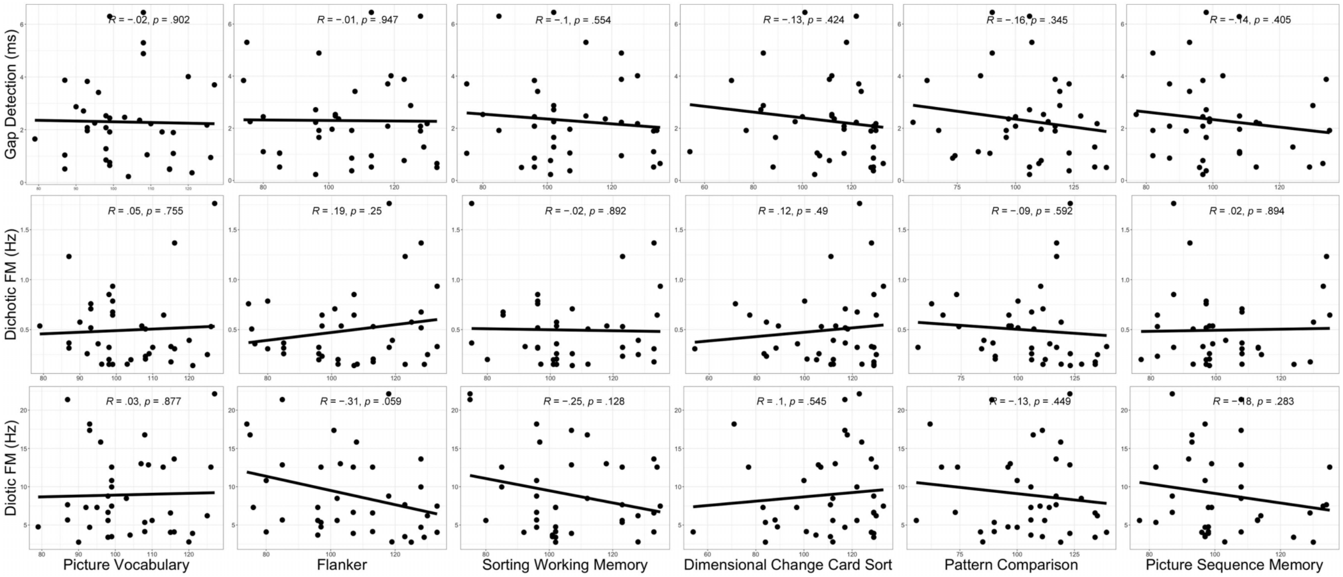


(A) Dichotic FM (B) Gap detection (C) Diotic FM



(D) Spectral Modulation (E) Temporal Modulation (F) Spectrotemporal Modulation

Figure 3. Scatter plots describing the relationship between the cognitive tests, that is, Picture Vocabulary, Flanker, Sorting Working Memory, Dimensional Change Card Sort, Pattern Comparison, and Picture Sequence Memory, and the tests for temporal fine structure perception, that is, Gap Detection, Dichotic Frequency Modulation (FM), and Diotic FM.



Relationship Between Cognitive Abilities and STS Perception

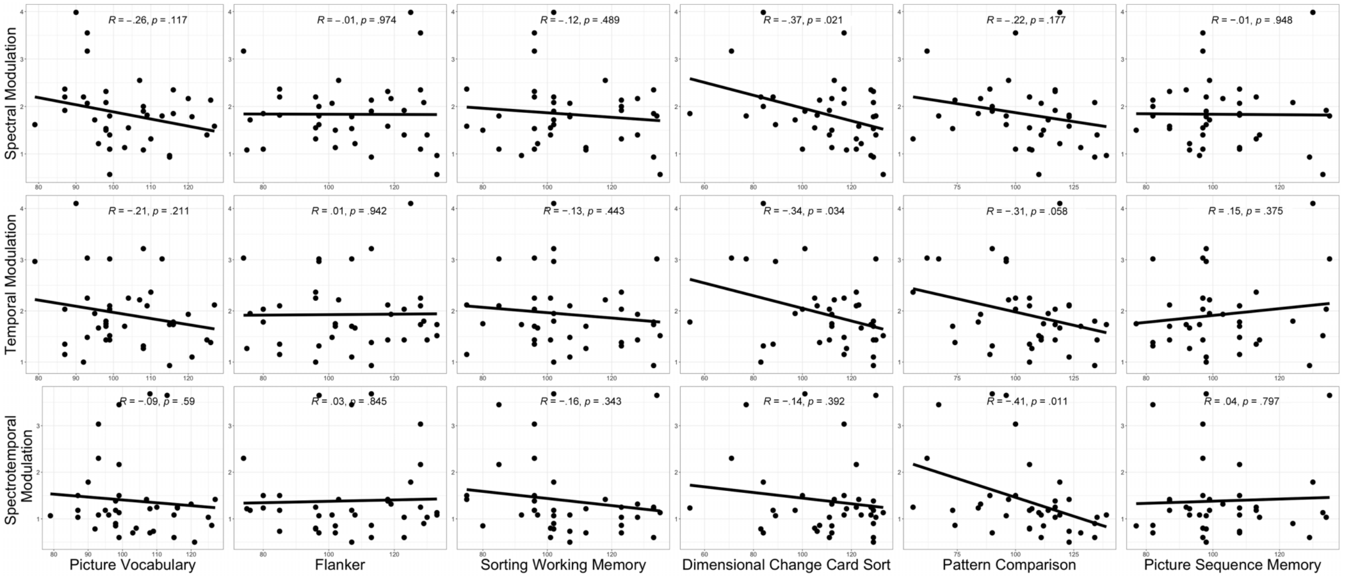
Overall, it was found that there was no significant correlation between the tests for cognitive abilities and tests for STS (see Figure 4 and Table 2). For a target corrected *p* value of < .0014, SM did not show any significant correlation with any of the cognitive tests, that is, Dimensional Change Card Sort (*R* = −.37, *p* = .021), Picture Vocabulary (*R* = −.26, *p* = .177), Flanker (*R* = −.01, *p* = .974), Sorting Working Memory (*R* = −.12, *p* = .489), Pattern Comparison (*R* = −.22, *p* = .177), and Picture Sequence Memory (*R* = −.01, *p* = .948). Similarly, TM did not show significant correlation with any of the cognitive tests, that is, Dimensional Change Card Sort (*R* = −.34, *p* = .034), Picture Vocabulary (*R* = −.21, *p* = .211), Flanker (*R* = .01, *p* = .942), Sorting Working Memory (*R* = −.13, *p* = .443), Pattern Comparison (*R* = −.31, *p* = .058), and Picture Sequence Memory (*R* = .15, *p* = .375). STM also exhibited no significant correlation with any of

Table 2. Correlation values of the tests of the PART battery with the tests of the National Institutes of Health (NIH) Toolbox Cognition Battery.

PART battery							
		Temporal fine structure			**Spectrotemporal sensitivity**		
		Gap detection	**Dichotic FM**	**Diotic FM**	**Spectral Modulation**	**Temporal Modulation**	**Spectrotemporal Modulation**
NIH Toolbox Cognition Battery	Picture Vocabulary	*R* = −.02, *p* = .902	*R* = .05, *p* = .755	*R* = .03, *p* = .877	*R* = −.26, *p* = .117	*R* = −.21, *p* = .211	*R* = −.09, *p* = .59
	Flanker	*R* = −.01, *p* = .947	*R* = .19, *p* = .25	*R* = −.31, *p* = .059	*R* = −.01, *p* = .974	*R* = .01, *p* = .942	*R* = .03, *p* = .845
	Sorting Working Memory	*R* = −.1, *p* = .554	*R* = −.02, *p* = .892	*R* = −.25, *p* = .128	*R* = −.12, *p* = .489	*R* = −.13, *p* = .443	*R* = −.16, *p* = .343
	Dimensional Change Card Sort	*R* = −.13, *p* = .424	*R* = .12, *p* = .49	*R* = .1, *p* = .545	*R* = −.37, *p* = .021	*R* = −.34, *p* = .034	*R* = −.14, *p* = .392
	Pattern Comparison	*R* = −.16, *p* = .345	*R* = −.09, *p* = .592	*R* = −.13, *p* = .449	*R* = −.22, *p* = .177	*R* = −.31, *p* = .058	*R* = −.41, *p* = .011
	Picture Sequence Memory	*R* = −.14, *p* = .405	*R* = .02, *p* = .894	*R* = −.18, *p* = .283	*R* = −.01, *p* = .948	*R* = .15, *p* = .375	*R* = .04, *p* = .797

Note. None of the correlations are significant. *p* value for significance should be < .0014, that is, adjusted for multiple comparisons. FM = Frequency Modulation; PART = Portable Auditory Rapid Testing.

Figure 4. Scatter plots describing the relationship between the cognitive tests, that is, Picture Vocabulary, Flanker, Sorting Working Memory, Dimensional Change Card Sort, Pattern Comparison, and Picture Sequence Memory, and the tests for Spectrotemporal sensitivity perception, that is, Spectral Modulation, Temporal Modulation, and Spectrotemporal Modulation.



the other cognitive tests, that is, Pattern Comparison (*R* = −.41, *p* = .011), Picture Vocabulary (*R* = −.09, *p* = .59), Flanker (*R* = .03, *p* = .845), Sorting Working Memory (*R* = −.16, *p* = .343), Dimensional Change Card Sort (*R* = −.14, *p* = .392), and Picture Sequence Memory (*R* = .04, *p* = .797).

Discussion

The current study aimed at evaluating the relationship between cognitive abilities and basic auditory processing abilities in young adults. More specifically, we conducted correlational analyses between Picture Vocabulary, Flanker, Sorting Working Memory, Dimensional Change Card Sort, Pattern Comparison, and Picture Sequence Memory components of the NIH Toolbox Cognition Battery with the tests of TFS (Gap Detection, Dichotic FM, and Diotic FM) and STS (SM, TM, and STM) from the PART battery (Gallun et al., 2018). Overall, we found no significant correlation between cognitive abilities and basic auditory processing in young adults.

The findings of the current study are in contrast with the previous studies that have found relationship of auditory processing with cognitive abilities (Krizman et al., 2012; Machado et al., 2018; Moore et al., 2014). For example, studies have found a top-down effect of executive function on auditory processing (Krizman et al., 2012; Machado et al., 2018). However, Krizman et al. (2012) studied bilinguals and found an enhanced auditory processing in them, as assessed via frequency following response, that was associated with enhanced executive functioning. Machado et al. (2018) found a significant correlation between executive functioning and auditory processing, but their subject group was adolescents with otitis media. Similarly, Moore et al. (2014) found a correlation between processing speed and speech perception in noise but their subject age range of 40–69 years.

Several studies on auditory processing (Ahmmed et al., 2014; Jain et al., 2023; Kumar et al., 2021; O'Brien et al., 2021; Riccio et al., 2005; Seeto et al., 2021; Tomlin et al., 2015) have found significant correlation of working memory with the measures of auditory processing. However, it should be noted that the measures/tests used in the previous studies could have already been loaded with components that needed employment of cognitive resources such as attention and working memory. For example, tests such as Spondaic Staggered Word that have been used in some of the studies (Cook et al., 1993; Riccio et al., 1994, 2005; Tillery et al., 2000) entail remembering the bisyllabic words presented simultaneously, one to each ear (e.g., *sunset* to right ear, *baseball* to left ear) with the second syllable of both words presented at the same time (i.e., *set* and *ball*), and to repeat/identify them correctly. In doing this task, individuals need allocation of their cognitive–linguistic resources and thus a correlation with auditory working memory scores is hardly surprising. Similarly, previous studies report that forward digit span, backward digit span, and auditory working memory exhibit significant correlation with dichotic digit and frequency pattern tests in children (Tomlin et al., 2015). On the contrary, in the current study, the tests were focused on basic sensory auditory processing that did not recruit the cognitive resources as much as the auditory tasks in the previous studies to exhibit a significant correlation. Along with the difference in the type of tests, another difference between the current and the previous studies is the type of population studied. Most of the previous studies that have exhibited a relationship between cognitive abilities and auditory processing have been conducted on children, both typical and those diagnosed with APD (Ferguson et al., 2011; Gyldenkærne et al., 2014; Keller et al., 2006; Moore et al., 2010; Riccio et al., 2005; Rosen et al., 2010; Sharma et al., 2009; Wilson et al., 2011). Apart from studies in children, studies involving older adults have also found significant correlations between cognitive abilities and auditory processing (Charney & Srinivasan, 2020; Grassi & Borella, 2013; Neils et al., 1991; O'Brien et al., 2021; Sheft et al., 2015). Based on the comparison between the current and the previous studies, it seems that the two main factors that could be driving the significant correlation between cognitive abilities and auditory processing is the complexity of the testing material used and the population age being tested. More generally, it seems that young children, older adults, and those with disorders (e.g., APD) need more involvement of cognitive resources in their processing of auditory information. On the other hand, young adults may not need as much involvement of cognitive resources for processing their auditory information—a finding that is visible in the current study.

The current findings have clinical implications in making recommendations on whether cognitive testing (beyond IQ measurement) is needed when testing for basic auditory processing. Based on the current findings, young adults seem to be generally immune to the effects of cognitive abilities on basic auditory processing, especially on the tests of STS and TFS. In comparison, during testing of children and older adults for APD, it seems that testing for cognitive abilities may prove useful, although there is a need for a large-scale study to be conducted comparing the correlation between cognitive abilities and auditory processing across children, young adults, and older adults.

Limitations and Future Directions

Although the current study contributes as a key preliminary step in investigating the link between auditory processing and cognitive abilities, there are some limitations and scope for future research. First, the sample size in current study is relatively small and thus, large-scale future studies are needed. Second, the current findings are based on young adults with typical auditory processing. Future studies need to be conducted in populations with impaired auditory processing. Third, future studies could also be conducted using the clinically available tests for auditory processing (e.g., speech in noise, dichotic sentences, etc.) to further understand the link between central auditory processing and cognitive abilities.

Data Availability Statement

Data can be made available on request.

Acknowledgments

The current work was funded by the Faculty Research and Development Grant at Hofstra University to Akshay R. Maggu. The authors would like to thank Melina Giorgou and Mansi Roy for their assistance with the study. The authors would also like to thank Frederick Gallun and Yue He for their support in setting-up of the PART battery routines at the beginning of the study.

References

Ahmmed, A. U., Ahmmed, A. A., Bath, J. R., Ferguson, M. A., Plack, C. J., & Moore, D. R. (2014). Assessment of children with suspected auditory processing disorder: A factor analysis study. *Ear and Hearing, 35*(3), 295–305. https://doi.org/10.1097/01.aud.0000441034.02052.0a

American Academy of Audiology. (2010). *Clinical practice guidelines: Diagnosis, treatment, and management of children and adults with central auditory processing disorder*. https://audiology-web.s3.amazonaws.com/migrated/CAPD%20Guidelines%208-2010.pdf_539952af956c79.73897613.pdf [PDF]

American Speech-Language-Hearing Association. (2005a). *Central auditory processing disorders*. https://doi.org/10.1044/policy.TR2005-00043

American Speech-Language-Hearing Association. (2005b). *(Central) auditory processing disorders—The role of the audiologist*. https://doi.org/10.1044/policy.TR2005-00043

British Society of Audiology. (2018). *Position statement and practice guidance auditory processing disorder (APD)*. https://www.thebsa.org.uk/wp-content/uploads/2023/10/Position-Statement-and-Practice-Guidance-APD-2018.pdf [PDF]

Bernstein, J. G. W., Mehraei, G., Shamma, S., Gallun, F. J., Theodoroff, S. M., & Leek, M. R. (2013). Spectrotemporal modulation sensitivity as a predictor of speech intelligibility for hearing-impaired listeners. *Journal of the American Academy of Audiology, 24*(04), 293–306. https://doi.org/10.3766/jaaa.24.4.5

Cacace, A. T., & McFarland, D. J. (2008). *Controversies in central auditory processing disorder*. Plural.

Cacace, A. T., & McFarland, D. J. (2013). Factors influencing tests of auditory processing: A perspective on current issues and relevant concerns. *Journal of the American Academy of Audiology, 24*(7), 572–589. https://doi.org/10.3766/jaaa.24.7.6

Charney, L., & Srinivasan, N. K. (2020). Relationship between spatial release from masking and working memory. *Proceedings of*

Meetings on Acoustics, 42(1), Article 050006. https://doi.org/10.1121/2.0001384

Cook, J. R., Mausbach, T., Burd, L., Gascon, G. G., Slotnick, H. B., Patterson, B., Johnson, R. D., Hankey, B., & Reynolds, B. W. (1993). A preliminary study of the relationship between central auditory processing disorder and attention deficit disorder. *Journal of Psychiatry & Neuroscience, 18*(3), 130–137.

Curtin, F., & Schulz, P. (1998). Multiple correlations and Bonferroni's correction. *Biological Psychiatry, 44*(8), 775–777. https://doi.org/10.1016/s0006-3223(98)00043-2

Dawes, P., & Bishop, D. (2009). Auditory processing disorder in relation to developmental disorders of language, communication and attention: A review and critique. *International Journal of Language & Communication Disorders, 44*(4), 440–465. https://doi.org/10.1080/13682820902929073

Dawes, P., & Bishop, D. V. (2010). Psychometric profile of children with auditory processing disorder and children with dyslexia. *Archives of Disease in Childhood, 95*(6), 432–436. https://doi.org/10.1136/adc.2009.170118

de Wit, E., van Dijk, P., Hanekamp, S., Visser-Bochane, M. I., Steenbergen, B., van der Schans, C. P., & Luinge, M. R. (2018). Same or different: The overlap between children with auditory processing disorders and children with other developmental disorders: A systematic review. *Ear and Hearing, 39*(1), 1–19. https://doi.org/10.1097/AUD.0000000000000479

de Wit, E., Visser-Bochane, M. I., Steenbergen, B., van Dijk, P., van der Schans, C. P., & Luinge, M. R. (2016). Characteristics of auditory processing disorders: A systematic review. *Journal of Speech, Language, and Hearing Research, 59*(2), 384–413. https://doi.org/10.1044/2015_JSLHR-H-15-0118

Dias, K. Z., Jutras, B., Acrani, I. O., & Pereira, L. D. (2012). Random Gap Detection Test (RGDT) performance of individuals with central auditory processing disorders from 5 to 25 years of age. *International Journal of Pediatric Otorhinolaryngology, 76*(2), 174–178. https://doi.org/10.1016/j.ijporl.2011.10.022

Diedesch, A. C., Bock, S. J. A., & Gallun, F. J. (2021). Clinical importance of binaural information: Extending auditory assessment in clinical populations using a portable testing platform. *American Journal of Audiology, 30*(3), 655–668. https://doi.org/10.1044/2021_AJA-20-00168

Dillon, H., & Cameron, S. (2021). Separating the causes of listening difficulties in children. *Ear and Hearing, 42*(5), 1097–1108. https://doi.org/10.1097/AUD.0000000000001069

Dillon, H., Cameron, S., Tomlin, D., & Glyde, H. (2014). Comments on "Factors influencing tests of auditory processing: A perspective on current issues and relevant concerns" by Tony Cacace and Dennis McFarland. *Journal of the American Academy of Audiology*, *25*(07), 699–703. https://doi.org/10.1055/s-0040-1715336

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16*(1), 143–149. https://doi.org/10.3758/BF03203267

Ferguson, M. A., Hall, R. L., Riley, A., & Moore, D. R. (2011). Communication, listening, cognitive and speech perception skills in children with auditory processing disorder (APD) or specific language impairment (SLI). *Journal of Speech, Language, and Hearing Research, 54*(1), 211–227. https://doi.org/10.1044/1092-4388(2010/09-0167)

Füllgrabe, C., Moore, B. C. J., & Stone, M. A. (2015). Age-group differences in speech identification despite matched audiometrically normal hearing: Contributions from auditory temporal processing and cognition. *Frontiers in Aging Neuroscience, 6,* Article 347. https://doi.org/10.3389/fnagi.2014.00347

Gallun, F. J., McMillan, G. P., Molis, M. R., Kampel, S. D., Dann, S. M., & Konrad-Martin, D. L. (2014). Relating age and hearing loss to monaural, bilateral, and binaural temporal sensitivity. *Frontiers in Neuroscience, 8,* Article 172. https://doi.org/10.3389/fnins.2014.00172

Gallun, F. J., Seitz, A., Eddins, D. A., Molis, M. R., Stavropoulos, T., Jakien, K. M., Kampel, S. D., Diedesch, A. C., Hoover, E., Bell, K., Souza, P. E., Sherman, M., Calandruccio, L., Xue, G., Taleb, N., Sebena, R., & Srinivasan, N. (2018). Development and validation of Portable Automated Rapid Testing (PART) measures for auditory research. *Proceedings of Meetings on Acoustics, 33*(1), Article 050002. https://doi.org/10.1121/2.0000878

Grassi, M., & Borella, E. (2013). The role of auditory abilities in basic mechanisms of cognition in older adults. *Frontiers in Aging Neuroscience, 5,* Article 59. https://doi.org/10.3389/fnagi.2013.00059

Grose, J. H., & Mamo, S. K. (2012). Frequency modulation detection as a measure of temporal processing: Age-related monaural and binaural effects. *Hearing Research, 294*(1–2), 49–54. https://doi.org/10.1016/j.heares.2012.09.007

Gyldenkærne, P., Dillon, H., Sharma, M., & Purdy, S. C. (2014). Attend to this: The relationship between auditory processing disorders and attention deficits. *Journal of the American Academy of Audiology, 25*(07), 676–687. https://doi.org/10.3766/jaaa.25.7.6

Hoover, E., Eddins, A. C., & Eddins, D. A. (2018). Distribution of spectral modulation transfer functions in a young, normal-hearing population. *The Journal of the Acoustical Society of America, 143*(1), 306–309. https://doi.org/10.1121/1.5020787

Hoover, E., Kinney, B. N., Bell, K. L., Gallun, F. J., & Eddins, D. A. (2019). A comparison of behavioral methods for indexing the auditory processing of temporal fine structure cues. *Journal of Speech, Language, and Hearing Research, 62*(6), 2018–2034. https://doi.org/10.1044/2019_JSLHR-H-18-0217

Hoover, E., Pasquesi, L., & Souza, P. (2015). Comparison of clinical and traditional gap detection tests. *Journal of the American Academy of Audiology, 26*(06), 540–546. https://doi.org/10.3766/jaaa.14088

Jain, C., Ghosh, P. G. V., Chetak, K. B., & Lakshmi, A. (2023). Relationship between central auditory processing abilities and working memory during adolescence. *Indian Journal of Otolaryngology and Head & Neck Surgery, 75*(1), 1–7. https://doi.org/10.1007/s12070-022-03126-w

Jerger, J., & Musiek, F. (2000). Report of the consensus conference on the diagnosis of auditory processing disorders in school-aged children. *Journal of the American Academy of Audiology, 11*(09), 467–474. https://doi.org/10.1055/s-0042-1748136

Keller, W. D., Tillery, K. L., & McFadden, S. L. (2006). Auditory processing disorder in children diagnosed with nonverbal learning disability. *American Journal of Audiology, 15*(2), 108–113. https://doi.org/10.1044/1059-0889(2006/014)

Krizman, J., Marian, V., Shook, A., Skoe, E., & Kraus, N. (2012). Subcortical encoding of sound is enhanced in bilinguals and relates to executive function advantages. *Proceedings of the National Academy of Sciences, 109*(20), 7877–7881. https://doi.org/10.1073/pnas.1201575109

Kumar, P., Singh, N. K., & Hussain, R. O. (2021). Effect of speech in noise training in the auditory and cognitive skills in children with auditory processing disorders. *International Journal of Pediatric Otorhinolaryngology, 146*. https://doi.org/10.1016/j.ijporl.2021.110735

Lelo de Larrea-Mancera, E. S., Stavropoulos, T., Carrillo, A. A., Cheung, S., He, Y. J., Eddins, D. A., Molis, M. R., Gallun,

F. J., & Seitz, A. R. (2022). Remote auditory assessment using Portable Automated Rapid Testing (PART) and participant-owned devices. *The Journal of the Acoustical Society of America, 152*(2), 807–819. https://doi.org/10.1121/10.0013221

Lelo de Larrea-Mancera, E. S., Stavropoulos, T., Hoover, E., Eddins, D. A., Gallun, F. J., & Seitz, A. R. (2020). Portable Automated Rapid Testing (PART) for auditory assessment: Validation in a young adult normal-hearing population. *The Journal of the Acoustical Society of America, 148*(4), 1831–1851. https://doi.org/10.1121/10.0002108

Machado, M. S., Teixeira, A. R., & da Costa, S. S. (2018). Correlation between cognitive functions and central auditory processing in adolescents with non-cholesteatomatous chronic otitis media. *Dementia & Neuropsychologia, 12*(3), 314–320. https://doi.org/10.1590/1980-57642018dn12-030013

Maggu, A. R., & Overath, T. (2021). An objective approach toward understanding auditory processing disorder. *American Journal of Audiology, 30*(3), 790–795. https://doi.org/10.1044/2021_AJA-21-00007

Mehraei, G., Gallun, F. J., Leek, M. R., & Bernstein, J. G. W. (2014). Spectrotemporal modulation sensitivity for hearing-impaired listeners: Dependence on carrier center frequency and the relationship to speech intelligibility. *The Journal of the Acoustical Society of America, 136*(1), 301–316. https://doi.org/10.1121/1.4881918

Miller, C. A., & Wagstaff, D. A. (2011). Behavioral profiles associated with auditory processing disorder and specific language impairment. *Journal of Communication Disorders, 44*(6), 745–763. https://doi.org/10.1016/j.jcomdis.2011.04.001

Moore, D. R. (2018). Guest editorial: Auditory processing disorder. *Ear and Hearing, 39*(4), 617–620. https://doi.org/10.1097/AUD.0000000000000582

Moore, D. R., Edmondson-Jones, M., Dawes, P., Fortnum, H., McCormack, A., Pierzycki, R. H., & Munro, K. J. (2014). Relation between speech-in-noise threshold, hearing loss and cognition from 40–69 years of age. *PLOS ONE, 9*(9), Article e107720. https://doi.org/10.1371/journal.pone.0107720

Moore, D. R., & Ferguson, M. A. (2014). It is neither necessary nor desirable to test for abnormalities in other modalities when diagnosing auditory processing disorder (APD). *Journal of the American Academy of Audiology, 25*(7), 697–698. https://doi.org/10.3766/jaaa.25.7.9

Moore, D. R., Ferguson, M. A., Edmondson-Jones, A. M., Ratib, S., & Riley, A. (2010). Nature of auditory processing disorder in children. *Pediatrics, 126*(2), e382–390. https://doi.org/10.1542/peds.2009-2826

Neils, J., Newman, C. W., Hill, M., & Weiler, E. (1991). The effects of rate, sequencing, and memory on auditory processing in the elderly. *Journal of Gerontology, 46*(2), P71–P75. https://doi.org/10.1093/geronj/46.2.P71

O'Brien, J. L., Lister, J. J., Fausto, B. A., Morgan, D. G., Maeda, H., Andel, R., & Edwards, J. D. (2021). Are auditory processing and cognitive performance assessments overlapping or distinct? Parsing the auditory behaviour of older adults. *International Journal of Audiology, 60*(2), 123–132. https://doi.org/10.1080/14992027.2020.1791366

Phillips, D. P., Comeau, M., & Andrus, J. N. (2010). Auditory temporal gap detection in children with and without auditory processing disorder. *Journal of the American Academy of Audiology, 21*(06), 404–408. https://doi.org/10.3766/jaaa.21.6.5

Riccio, C. A., Cohen, M. J., Garrison, T., & Smith, B. (2005). Auditory processing measures: Correlation with neuropsychological measures of attention, memory, and behavior. *Child Neuropsychology, 11*(4), 363–372. https://doi.org/10.1080/09297040490916956

Riccio, C. A., Hynd, G. W., Cohen, M. J., Hall, J., & Molt, L. (1994). Comorbidity of central auditory processing disorder and attention-deficit hyperactivity disorder. *Journal of the American Academy of Child and Adolescent Psychiatry, 33*(6), 849–857. https://doi.org/10.1097/00004583-199407000-00011

Rosen, S., Cohen, M., & Vanniasegaram, I. (2010). Auditory and cognitive abilities of children suspected of auditory processing disorder (APD). *International Journal of Pediatric Otorhinolaryngology, 74*(6), 594–600. https://doi.org/10.1016/j.ijporl.2010.02.021

Seeto, M., Tomlin, D., & Dillon, H. (2021). The relations between auditory processing scores and cognitive, listening and reading abilities. *Ear and Hearing, 42*(4), 803–813. https://doi.org/10.1097/AUD.0000000000000984

Sharma, M., Purdy, S. C., & Kelly, A. S. (2009). Comorbidity of auditory processing, language, and reading disorders. *Journal of Speech, Language, and Hearing Research, 52*(3), 706–722. https://doi.org/10.1044/1092-4388(2008/07-0226)

Sheft, S., Shafiro, V., Wang, E., Barnes, L. L., & Shah, R. C. (2015). Relationship between auditory and cognitive abilities in older adults. *PLOS ONE, 10*(8), Article e0134330. https://doi.org/10.1371/journal.pone.0134330

Sona Systems. (n.d.). *Sona systems: Cloud-based participant management software* [Computer software]. Retrieved 2023, from https://www.sona-systems.com/

Tillery, K. L., Katz, J., & Keller, W. D. (2000). Effects of methylphenidate (Ritalin) on auditory performance in children with attention and auditory processing disorders. *Journal of Speech, Language, and Hearing Research, 43*(4), 893–901. https://doi.org/10.1044/jslhr.4304.893

Tomlin, D., Dillon, H., Sharma, M., & Rance, G. (2015). The impact of auditory processing and cognitive abilities in children. *Ear and Hearing, 36*(5), 527–542. https://doi.org/10.1097/AUD.0000000000000172

Vermiglio, A. J. (2018). The gold standard and auditory processing disorder. *Perspectives of the ASHA Special Interest Groups, 3*(6), 6–17. https://doi.org/10.1044/persp3.SIG6.6

Viemeister, N. F. (1979). Temporal modulation transfer functions based upon modulation thresholds. *The Journal of the Acoustical Society of America, 66*(5), 1364–1380. https://doi.org/10.1121/1.383531

Weintraub, S., Bauer, P. J., Zelazo, P. D., Wallner-Allen, K., Dikmen, S. S., Heaton, R. K., Tulsky, D. S., Slotkin, J., Blitz, D. L., Carlozzi, N. E., Havlik, R. J., Beaumont, J. L., Mungas, D., Manly, J. J., Borosh, B. G., Nowinski, C. J., & Gershon, R. C. (2013). I. NIH Toolbox Cognition Battery (CB): Introduction and pediatric data. *Monographs of the Society for Research in Child Development, 78*(4), 1–15. https://doi.org/10.1111/mono.12031

Weintraub, S., Dikmen, S. S., Heaton, R. K., Tulsky, D. S., Zelazo, P. D., Slotkin, J., Carlozzi, N. E., Bauer, P. J., Wallner-Allen, K., Fox, N., Havlik, R., Beaumont, J. L., Mungas, D., Manly, J. J., Moy, C., Conway, K., Edwards, E., Nowinski, C. J., & Gershon, R. (2014). The Cognition Battery of the NIH Toolbox for assessment of neurological and behavioral function: Validation in an adult sample. *Journal of the International Neuropsychological Society, 20*(6), 567–578. https://doi.org/10.1017/S1355617714000320

Whiteford, K. L., Kreft, H. A., & Oxenham, A. J. (2017). Assessing the role of place and timing cues in coding frequency and amplitude modulation as a function of age. *Journal of the Association for Research in Otolaryngology, 18*(4), 619–633. https://doi.org/10.1007/s10162-017-0624-x

Whiteford, K. L., & Oxenham, A. J. (2015). Using individual differences to test the role of temporal and place cues in coding frequency modulation. *The Journal of the Acoustical Society of America, 138*(5), 3093–3104. https://doi.org/10.1121/1.4935018

Wilson, W. J., Jackson, A., Pender, A., Rose, C., Wilson, J., Heine, C., & Khan, A. (2011). The CHAPS, SIFTER, and TAPS-R as predictors of (C)AP skills and (C)APD. *Journal of Speech, Language, and Hearing Research, 54*(1), 278–291. https://doi.org/10.1044/1092-4388(2010/09-0273)

Zelazo, P. D. (2006). The Dimensional Change Card Sort (DCCS): A method of assessing executive function in children. *Nature Protocols, 1*(1), 297–301. https://doi.org/10.1038/nprot.2006.46