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Original Article

Relation between Working Memory Capacity and Auditory Stream Segregation in Children with Auditory Processing Disorder

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Abstract

Background: This study assessed the relationship between working memory capacity and auditory stream segregation by using the concurrent minimum audible angle in children with a diagnosed auditory processing disorder (APD).

Methods: The participants in this cross-sectional, comparative study were 20 typically developing children and 15 children with a diagnosed APD (age, 9–11 years) according to the subtests of multiple-processing auditory assessment. Auditory stream segregation was investigated using the concurrent minimum audible angle. Working memory capacity was evaluated using the non-word repetition and forward and backward digit span tasks. Nonparametric statistics were utilized to compare the between-group differences. The Pearson correlation was employed to measure the degree of association between working memory capacity and the localization tests between the 2 groups.

Results: The group with APD had significantly lower scores than did the typically developing subjects in auditory stream segregation and working memory capacity. There were significant negative correlations between working memory capacity and the concurrent minimum audible angle in the most frontal reference location (0° azimuth) and lower negative correlations in the most lateral reference location (60° azimuth) in the children with APD.

Conclusion: The study revealed a relationship between working memory capacity and auditory stream segregation in children with APD. The research suggests that lower working memory capacity in children with APD may be the possible cause of the inability to segregate and group incoming information.

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Keywords ● Auditory scene analysis ● Stream segregation ● Short-term memory ● Auditory perceptual disorders ● Child

What's Known

- Children with APD struggle to understand speech signals in the presence of noise. One possible reason for poor speech perception is a deficit in auditory stream segregation. The spatial features of competing sounds affect the segregation of target sounds.
- Stream segregation and extracting speech from competing noise is modulated cognitively by top-down mechanisms such as working memory.

What's New

- One possible reason for poor speech perception in children with APD is that they cannot benefit from spatial cues to segregate talkers from competing sounds.
- The present study showed the possible influence of working memory capacity on spatial cues and auditory stream segregation in children with APD.

Introduction

Auditory processing disorder (APD) is defined as difficulties in the processing of auditory information in the central nervous system[1] and is characterized by the poor localization, separation, grouping, discrimination, or ordering of sounds.[1,2] Children with APD have poor speech perception, especially in challenging environments. According to Jerger,[3] one possible reason for poor performance in multisource environments is a deficit in auditory figure-ground discrimination, the ability to pick out important sounds from a noisy background. Figure-ground discrimination can be related to the perceptual concept of auditory stream segregation.[4]

Sounds arriving at the ears usually come from different directions in space. Since all the surrounding sound signals arrive at the cochlea as a composite, a preliminary analysis of the incoming sound is required to divide the auditory input into distinct perceptual objects.[5] The ability of a listener to segregate a single target from a group of distracting signals is due to a process of perceptual organization known as stream segregation. The process by which sound properties are segregated from the acoustic background (auditory segregation) and then integrate together as discrete perceptual entities (auditory object representation) is known as auditory scene analysis (ASA).[5] Segregation and integration are 2 fundamental aspects of ASA. The ability to combine information from different sensory sources into unified concepts over time (integration processes) is a crucial part of ASA in that it allows the listener to understand speech. Working memory capacity plays a critical role in this process, especially because auditory processing relies on the temporal domain.

In general, the interplay between bottom-up and top-down mechanisms mediates ASA.[6,7] The separation between simultaneous sound events is based on numerous acoustic properties such as spectral, temporal, and spatial cues (bottom-up mechanisms).[8] Also, stream segregation is a dynamic process that is modulated cognitively by top-down mechanisms, which involve the organization of acoustic components into perceptual object representations based on prior experiences[9] or executive processes (especially working memory capacity and attention). Working memory capacity is defined as the ability to retain and manipulate information. Because speech perception requires the individual to follow, retain, and integrate a stream of auditory information, working memory capacity is likely to be a core component of speech perception.

The effect of the spatial features of competing sound sources on the segregation of target sounds has been known for several decades. The intelligibility of speech in the presence of background noise is higher when the speech and noise come from different sources. Different natural sound sources usually come from different directions in space, and localization cues are extensively used for the segregation of different talkers.[10] The ability to locate the spatial origin of a sound source requires the capacity of the central auditory nervous system to detect and compute a number of acoustic cues such as small differences in the arrival time and intensity of signals reaching the 2 ears. The interaural time differences of the low-frequency (<1.5 kHz) components of the sound provide a powerful cue for tracking speech signals on the horizontal plane (or azimuth).[11]

Previous studies have determined that extracting speech from competing noise requires working memory resources.[12] Their results suggest that competing auditory streams are less distracting to individuals with high working memory abilities; therefore, listeners with higher working memory capacity may be more adept at separating target signals from a complex situation.

Despite the rich history of research into directional hearing, only a few studies have attempted to measure the spatial resolution of the auditory system for simultaneous stimuli, particularly in children. In the present study, we used a measure of directional hearing known as the concurrent minimum audible angle, which is an excellent tool for measuring auditory segregation mediated by the binaural system. The concurrent minimum audible angle is defined as a threshold separation angle required to distinguish 2 stimuli that are presented simultaneously.[13] Perrott[14] measured the concurrent minimum audible angle in adults and found that the threshold separation angle significantly increased with laterality. In addition, the concurrent minimum audible angle increased from 4° to 10° at the front (0° azimuth) to 30° to 45° at a lateral displacement of 67°. Currently, little information is available on auditory streaming in children. The poor performance of children with APD in multisource environments may stem from their inability to benefit from spatial cues so as to judge the location of a sound source and segregate talkers from competing sounds. However, this issue has not been thoroughly investigated. Moreover, there is a paucity of data on the effects of cognitive processing such as working memory capacity on auditory segregation in children with APD. Therefore, we sought to investigate specifically (*a*) working memory capacity and auditory segregation using pairs of concurrent auditory stimuli and (*b*) the possible influence of working memory capacity on auditory segregation in children with APD and subsequently compare them with those in healthy controls.

Patients and Methods

Participants

The data on 15 right-handed children with APD (12 males and 3 females; mean age, 9.1 years; SD, 0.35) and 20 healthy control children (13 males and 7 females; mean age, 9.4 years; SD, 0.5) were included in this study. Children with APD were recruited from the audiology clinics of the University of Social Welfare and Rehabilitation. The subjects had a clinical diagnosis of APD according to the multiple-processing auditory assessment subtests. (For reviews, see Ronald L., 2007.)15 Clinical diagnoses were established by experienced clinicians on the basis of a careful developmental history taking and a battery of tests, comprising the dichotic digit test,16 pitch pattern sequence test, and monaural selective auditory attention test.17

The dichotic digit test is composed of naturally spoken digits from 1 to 10 (except for the number 4 in Farsi). The original formulation requires that 2 number pairs be presented simultaneously to each ear of the listener, with the subject being required to repeat all 4 numbers. Forty patterns are presented in total. The outcome measure is the percentage of the correct responses for each ear.[15]

The pitch pattern sequence test reflects the temporal component of auditory pattern recognition. The test presents 3 tones of 500 msec duration each and an interval of 10 seconds. Two of the tones are the same and one varies, and the subject is required to declare the pattern to the tester (verbally, by humming or by pointing to a visual analogue). A total of 30 patterns are presented monaurally to each ear following a brief practice session. The outcome measure is the percentage of the correct responses.[15]

The monaural selective auditory attention test compares the ability of the patient to recognize monosyllabic words embedded in a background of competing high-interest speech. Both the target and the competition stimuli are recorded by the same speaker, thereby eliminating speaker recognition cues. This version utilizes only monaural stimulation, as a monaural low-redundancy test. The outcome measure is the percentage of the correct responses for each ear.[15]

In order to assess relative homogeneity in children with APD, we included only children who displayed auditory deficits evidenced by poor performance on all 3 auditory tests in the study.

All the participants had normal hearing (better than 15 dB HL at octave frequencies between 250 and 8000 in the audiometry test)[18] and normal IQs (≥85 on the Wechsler Revised Intelligence Scale for children).[19] The subjects underwent a comprehensive general audiological assessment in order to provide background data. The results of otoscopy, tympanometry, and speech discrimination score were normal. None of the participants had a history of a neurological disease or injury. Subjects with a history of hearing impairment, ear diseases, and neurological difficulties were excluded from our study. All the subjects gave consent prior to participation in this research. This study was approved (#1429) by the local ethics committee of the University of Social Welfare and Rehabilitation.

Procedures

Children who fulfilled the selection criteria were subjected to working memory capacity assessment and auditory stream segregation task. All the tests were performed under controlled test conditions in a sound-treated room with an ambient noise level <30 dBA. Each child was evaluated individually in a single 1-hour session.

Working memory capacity is commonly assessed by determining the number of items (i.e., letters, words, or sentences) that a person can keep in mind simultaneously for a short period of time. Both the phonological loop and the central executive (components of working memory capacity)[20] were assessed in this study. Two of the most reliable measures of the phonological loop and verbal working memory capacity that are widely used in studies are forward digit span and non-word repetition tasks. The central executive is assessed using backward digit span.[21] Forward digit span assesses both attention and short-term memory capacity, whereas backward digit span measures working memory capacity.[22]

Forward and backward digit spans were obtained using the digit span subtests of the Wechsler Intelligence Scale for children.[23] In each case, digit span was measured for the forward and backward (reverse-order) recall of the digit sequences. The number of the digits was increased from 3 to 9 for forward digit span and from 2 to 8 for backward digit span, and 2 trials using different digit sets were presented at each increasing list length. Testing was ceased when the subject failed to accurately report either trial at 1 sequence length or when the maximal list length was reached (9 digits forward and 8 backward).

The validated Farsi non-word repetition task[24] was used in this study. The test consisted of 40 non-words, which ranged in length from 1 to 4 syllables. The subjects were instructed to repeat the non-word that they had just heard. Performance in this task was analyzed by counting the error percent for each non-word length.

In this study, auditory stream segregation was assessed using a method described by

Best[13] (2004).In this method, a 2-trial forced-choice procedure was employed. The subjects were presented with 2 simultaneous tones of different frequencies (i.e., 500 Hz and 800 Hz) and were asked to judge the relative location of the pair by indicating whether the higher tone was to the left or right of the lower tone, on the right hand side of the subjects (Figure 1). The subjects' head was positioned in the center. The subjects were instructed to keep their heads in this position for the duration of the recording process (about 15 min). Testing took place using 3 reference locations on a horizontal plane: 0°, 30°, and 60°. For each reference location, 10 test locations were chosen on the basis of preliminary testing. In each trial, a pair of concurrent stimuli was presented. One stimulus corresponded to 1 of the reference locations, and the second stimulus was presented from 1 of the 10 test locations displaced in either azimuth. Prior to data acquisition, the subjects completed training blocks to ensure that they were able to detect the targets. Using a criterion of 75% correct in each test location, we measured the concurrent minimum audible angle. Stimuli were generated using MATLAB (The MathWorks, Natick, MA) and Sound Forge software (v.10 by Sonic Foundry) with a sampling rate of 44.1 kHz. The stimuli were presented through headphones (TDH 39) via an audiometer, at 50 dB SL.

Statistical Analysis

All the analyses were conducted using Statistical Package for the Social Sciences (SPSS), version 16. Due to the relatively small group numbers in the study, the data did not meet normality assumptions in general. Therefore, nonparametric statistics (Mann–Whitney U) were used to compare the between-group differences. The Pearson correlation was employed to measure the degree of association between working memory capacity and the localization tests. The significance level adopted was 0.05 (5%), with confidence intervals of 95%.

Results

Auditory Processing Tests

The mean scores and SDs for the pitch pattern sequence test, dichotic digit test, and monaural selective auditory attention test for the children with APD and the typically developing children are shown in Figure 2.

Working Memory Capacity Tests

The mean scores and SDs for the non-word repetition and forward and backward digit span tasks for the children with APD and the typically developing children are depicted in Figure 3. In the non-word repetition task, the control group had near-ceiling scores, whereas the group

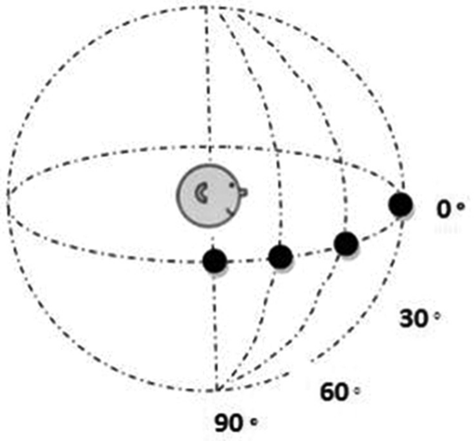

Figure 1: Schematic diagram of the reference positions around the head on the horizontal plane for the measurement of the concurrent minimum audible angle. The black dots illustrate the 3 reference locations examined: 0°, 30°, and 60° azimuth, all on the 0 ° elevation plane at the level of the ears.

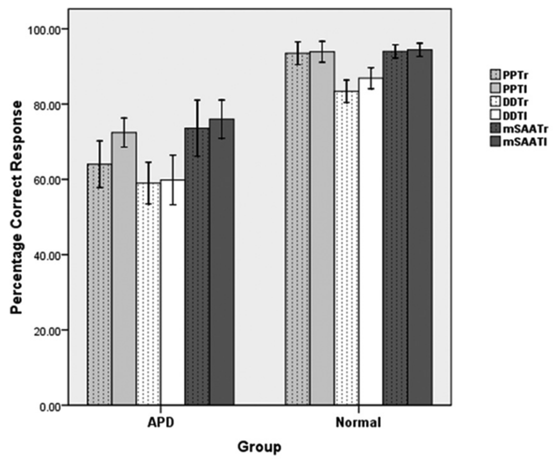

Figure 2: Bar charts comparing the performance of the group with audio processing disorder (APD) with that of the control group on the 3 auditory processing tasks for each ear.

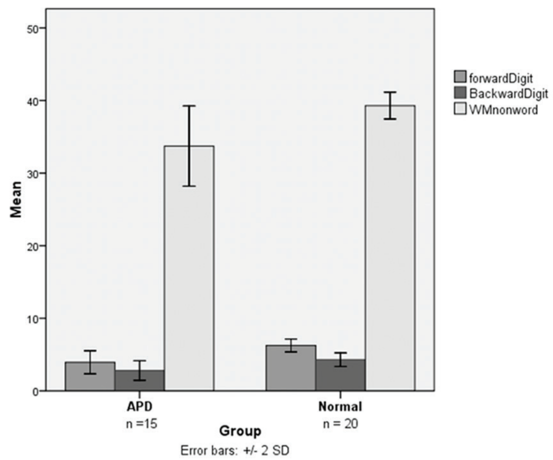

Figure 3: Means and SDs of the non-word repetition and forward and backward digit span tasks for the group with audio processing disorder (APD) and the control group.

with APD had markedly lower scores. Both the forward and backward digit span scores were higher in the typically developing children than in the group with APD. The forward digit span scores were higher than were the backward digit span scores in both groups. Between-group comparisons revealed that the group with APD had a significantly lower score than did the control group in all the working memory capacity tests (P<0.001).

Auditory System Segregation

Table 1 shows the descriptive and inferential statistics of the concurrent minimum audible angle for the children with APD and the typically developing children. The concurrent minimum audible angle increased as a function of the laterality of the sources in both groups. Between-group comparisons revealed that the group with APD had a significantly greater change for the separation of the concurrent stimuli than did the typically developing children on the 0° and 30° reference locations (P<0.05). At the most lateral reference location in this study (i.e., 60° azimuth), there was no significant difference between the 2 groups (P=0.538).

Correlations between Working Memory Capacity and the Concurrent Minimum Audible Angle

Table 2 presents the correlations between the working memory capacity tasks (i.e., non-word repetition task and forward and backward digit span tasks) and the concurrent minimum audible angle in the group with APD. The results in the children with APD showed higher negative correlations of the working memory capacity variables with the concurrent minimum audible angle results in the most frontal reference location (0° azimuth) and lower negative correlations in the most lateral reference location (60° azimuth). The results showed that the forward digit span task had significant correlations with the concurrent minimum audible angle in the 0° and 30° reference positions (P=0.03 and P=0.05, respectively). The non-word repetition task had a significant correlation only with the concurrent minimum audible angle in the 0° reference position (P=0.04). There were no correlations between the working memory capacity tasks and the concurrent minimum audible angle in the 60° reference position (P>0.05).

Table 3 demonstrates the correlations between the working memory capacity tasks and the concurrent minimum audible angle in the control group. As can be seen, the correlations were different between the typically developing children and those with APD. The results for the typically developing children showed that there were no significant correlations between the working memory capacity tasks and the concurrent minimum audible angle in all the reference positions (P>0.05).

Table 1: Means and SDs of the CMAA for the children with APD and the typically developing children

Variable	Mean±SD		P value
	Children with APD n, 15	Typically developing children n, 20	
CMAA 0°	17.53±5.38	13.35±2.84	0.014[a]
CMAA 30°	35.50±5.14	20.75±3.8	<0.000[a]
CMAA 60°	49.13±5.08	45.87±4.39	0.538

[a]P<0.05; CMAA: Concurrent minimum audible angle; APD: Audio processing disorder

Table 2: Correlations between the working memory capacity tasks and the concurrent minimum audible angle in the children with APD

Group with APD n, 15	Concurrent minimum audible angle		
	0° (P value)	30° (P value)	60° (P value)
Non-word	−0.57 (0.04)[a]	−0.38 (0.16)	−0.19 (0.50)
Forward digit	−0.56 (0.03)[a]	−0.51 (0.05)[a]	−0.17 (0.57)
Backward digit	−0.42 (0.12)	−0.16 (0.56)	−0.08 (0.77)

[a]P<0.05; APD: Audio processing disorder

Table 3: Correlations between the working memory capacity tasks and the concurrent minimum audible angle in the typically developing children

Typically developing group n, 20	Concurrent minimum audible angle		
	0 ° (P value)	30 ° (P value)	60 ° (P value)
Non-word P value	−0.15 (0.53)	−0.02 (0.90)	−0.002 (0.99)
Forward digit P value	−0.34 (0.14)	−0.11 (0.63)	−0.13 (0.54)
Backward digit P value	−0.28 (0.23)	−0.05 (0.81)	−0.13 (0.58)

P<0.05

Discussion

The findings of the current study revealed that the children with APD were significantly poorer than were the control group in both working memory capacity measures and auditory stream segregation according to the concurrent minimum audible angle.

Working memory capacity deficits in children with APD have been reported in some studies. Maerlender et al.[25] showed poor performance in forward and backward digit span tasks in children diagnosed with APD. In a different study, Iliadou and Bamiou[26] found that the working memory capacity of their children with APD, as measured by non-word repetition and forward and backward digit span tasks, was significantly poorer than that of their control group. These findings support our results indicating poor working memory capacity in children with APD by comparison with typically developing children. This finding is line with the hypothesis that APD cannot be defined as an exclusively modality-specific perceptual dysfunction because the brain is non-modular and the auditory sensory processing in the central nervous system modulated by top-down mechanism influences working memory capacity.[1]

Previous studies have shown that that performance in spatial discrimination tasks becomes poorer in the horizontal dimension as the azimuth increases.[13,27] The results of the present study indicated that at a more lateral reference point (i.e., 60°), the angle of separation increased in both the typically developing children and the children with APD. These data are consistent with those reported by some previous studies which have shown that the concurrent minimum audible angle of tones increases in the lateral position.[14] The findings of our study showed that the value of the concurrent minimum audible angle increased as the reference location was moved laterally (60° azimuth) in both groups; nonetheless, the children with APD required a greater change for the separation of concurrent stimuli than did the typically developing children in all the reference locations, especially in the 0° and 30° reference points.

The results of the current study revealed significant differences between the 2 groups in the 0° and 30° reference positions, but there was no significant difference in the 60° azimuth reference point. This may be due to the fact that the concurrent minimum audible angle is most acute for sounds presented directly in front of the subject and least sensitive when the stimuli are presented from the lateral side.

Currently, there is no information on the effects of cognitive processing such as working memory capacity on auditory segregation using the concurrent minimum audible angle in children with APD. We found significant negative correlations between working memory capacity and the concurrent minimum audible angle in the most frontal reference location (0° azimuth) and lower negative correlations in the most lateral reference location (60° azimuth) in our children with APD. This finding suggests that interventions designed to enhance the individual's cognitive strategies such as working memory capacity may confer better performance in the concurrent minimum audible angle in the frontal reference locations. There were no significant correlations between the concurrent minimum audible angle and working memory capacity in the control group. The difference between the 2 groups may be explained by the notion that in children with lower working memory capacity, the top-down system must work harder and rely more on the bottom-up system to make sense of the acoustic information. This finding underscores the importance of a specific top-down rehabilitation program based on working memory capacity enhancement in children with APD.

Conway et al.[28] demonstrated that the subjects with high working memory capacity did better on the auditory processing task (dichotic listening) than did those with low working memory capacity in their study. The findings of the present study are in line with studies which have suggested that working memory capacity underlies the auditory processing performance.

Previous investigations have demonstrated that accurate segregation can be impaired in a noisy environment because the non-target signals place a cognitive load on working memory capacity.[29] Since working memory is a capacity-limited system and capacity comprises processing and storage components, any excessive load for processing due to difficult auditory task and noisy environment will decrease the share of storage component.[30] The current study showed that potentially lower working memory capacity in the children with APD could be the reason for their inability to segregate and group information binaurally and presumably for their listening difficulties in multisource environments. The findings of the present study support the hypothesis that competing auditory streams are more distracting to individuals with low working memory abilities.

There are some limitations in the current study. This study had a relatively small sample size, which suggests the need for further studies with larger samples. We could not match the intelligence factor between the 2 groups due to the small sample size, although there was no significant difference between the 2 groups (IQ range, 92 to 105). It should be noted that because APD can range in varying degrees of significance and may coexist with other disabilities, it may be difficult to diagnose "pure" APD correctly. Accordingly, the term "suspected APD" may be more appropriate for some cases of this research. Future studies using working memory capacity paradigms with incremental difficulty loads (e.g., white noise and speech noise) may enhance our understanding of the relationship between working memory capacity and auditory stream segregation.

Conclusion

Working memory capacity was lower in the children with APD than in the age-matched, normal-hearing children in the present study. Moreover, the group with APD had poorer performance in the concurrent minimum audible angle skills for all 3 reference positions (i.e. 0°, 30°, and 60°), especially in the more lateral position. The results of this study revealed significant negative correlations between working memory abilities and auditory stream segregation skills. Poor working memory capacity in children with APD may be the possible cause of poor performance in the segregating and grouping of incoming information and in turn poor speech perception in complex and noisy environments. Our findings suggest that higher-order dysfunction or inadequate top-down factors such as working memory capacity in children with APD may have a negative effect on their ability to perform auditory stream segregation, not least in challenging environments. Since cognitive systems interact with auditory processing and speech comprehension, clinicians should employ multiple measures (bottom-up and top-down) for children with APD so that management may be beneficial for them. The findings of this study offer support for further research into the potential benefits of auditory working memory training to improve auditory stream segregation abilities in persons with APD. Individuals with APD require comprehensive assessment and an intervention program specifically for each individual's needs. Furthermore, clinicians should manage these children' specific behaviors and work on their weaknesses.

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Conflict of Interest: None declared.

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