Attention, Memory, and Auditory Processing in 10- to 15-Year-Old Children With Listening Difficulties

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Purpose: The aim of this study was to examine attention, memory, and auditory processing in children with reported listening difficulty in noise (LDN) despite having clinically normal hearing.

Method: Twenty-one children with LDN and 15 children with no listening concerns (controls) participated. The clinically normed auditory processing tests included the Frequency/Pitch Pattern Test (FPT; Musiek, 2002), the Dichotic Digits Test (Musiek, 1983), the Listening in Spatialized Noise—Sentences (LiSN–S) test (Dillon, Cameron, Glyde, Wilson, & Tomlin, 2012), gap detection in noise (Baker, Jayewardene, Sayle, & Saeed, 2008), and masking level difference (MLD; Wilson, Moncrieff, Townsend, & Pillion, 2003). Also included were research-based psychoacoustic tasks, such as auditory stream segregation, localization, sinusoidal amplitude modulation (SAM), and fine structure perception. All were also evaluated on attention and memory test batteries.

Results: The LDN group was significantly slower switching their auditory attention and had poorer inhibitory control. Additionally, the group mean results showed significantly poorer performance on FPT, MLD, 4-Hz SAM, and memory tests. Close inspection of the individual data revealed that only 5 participants (out of 21) in the LDN group showed significantly poor performance on FPT compared with clinical norms. Further testing revealed the frequency discrimination of these 5 children to be significantly impaired.

Conclusion: Thus, the LDN group showed deficits in attention switching and inhibitory control, whereas only a subset of these participants demonstrated an additional frequency resolution deficit.

Some children, in spite of normal hearing sensitivity, report persistent listening difficulties, especially in noisy environments, such as classrooms (Hind et al., 2011; Lagacé, Jutras, & Gagné, 2010; D. R. Moore, Rosen, Bamiou, Campbell, & Sirimanna, 2013). In addition to hearing sensitivity, listening in background noise has been suggested to also depend on abilities such as attention, auditory processing, and memory (Bronkhorst, 2000; Brungart & Simpson, 2007; Conway, Cowan, & Bunting, 2001; Haykin & Chen, 2005; McDermott, 2009). The aim of the current study was to evaluate a range of auditory processing and cognitive functions focusing on attention and memory in children with reported listening difficulty in the presence of background noise. To be clear, in the context of this study, noise refers to the sound produced by a range of talker and nontalker sources, not just a speech spectrum random noise, and contains both energetic and informational masking elements (Kidd, Mason, Richards, Gallun, & Durlach, 2008).

Auditory attention is an important factor influencing the ability to listen in the presence of background noise (Fritz, Elhilali, David, & Shamma, 2007; Sturm, Willmes, Orgass, & Hartje, 1997). Evidence for attention deficits in children with listening difficulties has been shown in two recent studies (Dhamani, Leung, Carlile, & Sharma, 2013; D. R. Moore, Ferguson, Edmondson-Jones, Ratib, & Riley, 2010). Auditory attention includes phasic alertness, sustained attention, selective attention, and attention switching ability (Gomes, Molholm, Christodoulou, Ritter, & Cowan, 2000; Sturm et al., 1997). In a majority of listening situations involving multiple talkers and distractors, there is temporal overlap of different sources in different spatial locations. Such situations require the listener to selectively focus attention to the target information (selective attention) and to switch focus between different sources of information (attention switching).
on the basis of their relevance (Astheimer & Sanders, 2009). In our earlier study (Dhamani et al., 2013), we designed a psychophysical paradigm that revealed substantially longer attention reorientation time, which may be the basis for poor attention switching ability in children with listening difficulties in background noise.

There have also been suggestions that a proportion of children who complain of listening difficulties especially in noise may have deficits in auditory processing (Bamiou, Musiek, & Luxon, 2001; Lagacé et al., 2010; D. R. Moore et al., 2013). Auditory processing is an umbrella term encompassing a variety of auditory skills. Clinical guidelines suggest evaluating localization, lateralization, auditory discrimination, auditory temporal processing, auditory pattern processing, dichotic auditory performance in competing acoustic signals, and auditory performance with degraded acoustic signals (Musiek et al., 2010). In the work reported here, we also tested our group of listeners with listening difficulty in noise (LDN) for auditory processing deficits using a set of normed clinical tests as well as tests that are not yet clinically normed with a view to identifying which auditory processing abilities may be linked to their complaint of difficulties listening in noise (Musiek et al., 2010).

The recommended clinical test battery used by audiologists to evaluate children with listening difficulties usually encompasses a wide range of auditory processing and cognitive skills (Emanuel, 2002; Jerger & Musiek, 2000; Musiek et al., 2010). Although suggested in literature to be crucial to listening in noise, some additional skills—such as frequency resolution, auditory stream segregation, localization, temporal envelope/fine structure perception, and auditory short-term/working-memory skills—are not routinely assessed for children with listening difficulties (Musiek et al., 2010; Parthasarathy, 2006).

Some studies report that listeners with dyslexia and language impairment also have difficulty listening in background noise (Alcántara, Weisblatt, Moore, & Bolton, 2004; Ziegler, Pech-Georgel, George, & Lorenzi, 2009, 2011). These populations reportedly demonstrate deficits in auditory stream segregation (Démondet, Batty, Chaix, & Taylor, 2006; Helenius, Utela, & Hari, 1999; Lepistö et al., 2009), frequency resolution (Halliday & Bishop, 2006; McArthur & Bishop, 2004), and temporal envelope processing (Cohen-Mimran & Saper, 2007; Rocheron, Lorenzi, Füllgrabe, & Dumont, 2002). Thus, in the current study, auditory processing skills were assessed on this additional set of tasks—namely, frequency resolution, auditory stream segregation, temporal envelope/fine structure perception, and localization.

There is some evidence that memory deficits may underlie difficulties with listening in noise (Gathercole & Alloway, 2005; Montgomery, Magimairaj, & Finney, 2010; Nelson & Warrington, 1980). Auditory short-term and working-memory skills likely facilitate speech understanding in the presence of noise by allowing the listener to temporarily store information across time and to form coherent representations while ignoring irrelevant distractions (Arlinger, Lunner, Lyxell, & Pichora-Fuller, 2009; Conway et al., 2001; Kraus, Strait, & Parbery-Clark, 2012; Pichora-Fuller, Schneider, & Daneman, 1995). This is consistent with earlier studies conducted on adult listeners indicating that the performance on speech recognition in competing speech is strongly correlated to verbal working memory skills (Kraus et al., 2012; Meister et al., 2013; Rudner, Lunner, Behrens, Sundewall Thorén, & Rönberg, 2012).

In summary, different groups of participants with reported complaints of listening in noise have been shown previously, across various studies, to have deficits in auditory processing and some cognitive abilities. The current study aimed to investigate auditory processing and cognitive abilities—such as attention switching and/or memory deficits—in a group of school-age children with reported difficulties listening in noise.

**Method**

**Participants**

Fifteen children (10–15 years of age; 12.5 ± 1.6 [M ± SD]) with no listening difficulty (control group) and 21 children (10–15 years of age; 12.3 ± 1.9) with self-, teacher, and parental reports of listening difficulties in noisy backgrounds (LDN group) participated in the current study. The LDN group was recruited through an advertisement published in a local magazine freely available to families and routinely used for recruitment of child participants. In addition, information brochures were also provided to parents, family, and friends of children referred to the Macquarie University audiology clinic. All participants spoke English as their first language and had normal hearing sensitivity (250–8000 Hz) on clinical evaluation. None of the participants presented with middle ear pathology at the time of testing, which was confirmed by clinically normal findings for otoscopy, tympanometry, pure tone audiometry, and acoustic stapedial reflex thresholds. Participants who had a history or formal diagnosis of attention-deficit/hyperactivity disorder were excluded from this study.

**Procedures**

A questionnaire (see the Appendix) was provided to the parents of all the participants to gather information regarding their child’s academic, hearing, listening, and behavioral history. Additionally, the parents were also asked to rate their child’s overall hearing, listening, attention, memory, as well as reading ability on an informal rating scale (scale of 0–5; 0 = very good, and 5 = very poor).

Each test session was 3 hr in duration, and all the testing was distributed across 3–4 sessions within a 2-week period. Care was taken to avoid participant fatigue and loss of motivation by constant engagement with the participants, breaks, and positive reinforcement. To avoid bias and fatigue effects, the test order was randomized, and ears were counterbalanced. All the sounds used in the research were generated on a personal computer at a 48000-Hz sampling rate (16 bits) and were routed via a USB-based computer sound interface (RME Fireface 400) connected to either headphones (Beyerdynamic DT 990 Pro) or loudspeakers...
(Tannoy V6). The stimuli that were used to assess auditory processing skills were selected with an aim to minimize the influence of prior linguistic knowledge or language competency on performance. All participants underwent the same number of practice trials for each of the tasks to ensure that they were well understood. Informed consent was obtained from all participants, and the study was conducted in compliance with the guidelines of the Human Research Ethics Committee at Macquarie University.

**Attention, Memory, and Auditory Processing**

**Selective attention and attention switching task.** Using a button press, participants identified when the target syllable (/da/) appeared in a sequence of five syllables /da, ga, ka, ba, pa/ presented with competing two-talker speech babble. A 2.5-kHz tone was presented as a cue just prior to the first syllable of the sequence. The syllables within the sequence were 150 ms long and were pseudorandomly presented such that no syllable was presented twice within each sequence. The target /da/ syllable was presented 60% of the time as first in the sequence and was presented less frequently (20%) at other positions in the sequence (see Figure 1), with 20% of the time the target did not appear in the sequence (catch trials). The responses of the participants were then analyzed in the form of pooled hit and false-alarm rates (Werner, Parrish, & Holmer, 2009). The values of hit and false-alarm rates are represented as $M \pm SE$. Pooled statistics were calculated for each epoch in the sequence (Macmillan & Creelman, 2005; Macmillan & Kaplan, 1985; significant difference ($p < .05$) was indicated by a lack of overlap of the 95% confidence intervals (Werner et al., 2009).

**Sustained attention and memory.** All participants were tested for sustained auditory attention using an auditory continuous performance test (Keith & Engineer, 1991; Riccio, Cohen, Hynd, & Keith, 1996). Auditory memory was assessed on the basis of a digit span test, including both forward and backward digits (Lezak, Howieson, & Loring, 2004). The digit span test is part of the **Clinical Evaluation of Language Fundamentals, Fourth Edition** (Semel, Wiig, & Secord, 2003), and it measures short-term and working-memory performance (Harris et al., 2013; St Clair-Thompson, 2010). The forward digit task requires the listener to recall numbers in correct serial order after hearing the numbers, and the backward task requires the listener to repeat the numbers in the last to first order. The numbers were recorded in a monotone voice by an Australian female speaker and were presented at a rate of one per second. The length of the series was increased until the listener failed to repeat the series in the required order.

**Auditory processing skills.** The clinically normed test battery consisted of the Frequency/Pitch Pattern Test (FPT; Musiek, 2002), the Dichotic Digits Test (DDT; Musiek, 1983), the binaural masking level difference (MLD; Wilson, Moncrieff, Townsend, & Pillion, 2003), gap detection in noise (Baker, Jayewardene, Sayle, & Saeed, 2008), and the Listening in Spatialized Noise—Sentences (LiSN–S) test (Dillon, Cameron, Glyde, Wilson, & Tomlin, 2012; see Table 1). Performance was compared with previously published age-based normative data (Bellis, 2003; Kelly, 2007).

**Figure 1.** Schematic of a stimulus block used for the attention switching task. The x-axis shows the amplitude or intensity of the syllables, whereas the y-axis shows the time of the syllable presented in each train. The rectangular block is representative of the pure tone cue of 2.5 kHz. Following this, a sequence of five syllables (/da, pa, ga, ka, pa/; numbered 1–5) was randomly presented in two-talker speech babble presented at signal-to-noise ratios in which about 70%–85% speech recognition accuracy was achieved. The target syllable (/da/) was presented 60% of the time and 5% at the other four epochs with 20% catch trials in which syllables other than /da/ were presented.
The research based psychoacoustic tasks included auditory stream segregation, spatial localization, temporal envelope perception, as well as temporal fine structure perception (see Table 2). Further details are provided in the online supplemental materials. These tasks were chosen for their use of nonspeech stimuli, their use of adaptive technique, and their links to speech perception in noise (Cohen-Mimran & Sapir, 2007; Démonet et al., 2006; Halliday & Bishop, 2006). Furthermore, these tasks expanded the clinical test battery and investigated temporal envelope detection, temporal fine structure, and spectral resolution. The participants were tested twice within a span of 2 weeks on psychoacoustic tasks only when they showed variable track widths to ensure that poor performance on any given task was due to nonauditory variables, such as fatigue.

Results and Discussion

The control and LDN groups showed no significant difference between ages ($p > .05$). Parental ratings on the questionnaire showed, unsurprisingly, that the LDN group was significantly lower compared with the control group for attention and memory ($p = .001$), listening ability in quiet ($p = .004$), and listening in noise ability ($p < .001$). Clinical populations “willing” to participate in a study or questionnaire may introduce a recruitment bias, so they may have more/worse perceived or otherwise deficits (McCullagh & Feinstein, 2003). Selection bias can be reduced by large sample, population studies (Torgerson, 2001), especially if the aim is to identify the link between perceived difficulty and behavioral performance. The aim of the current study was to determine whether deficits in auditory processing, memory, and/or attention might explain participants’ listening deficits in noise. The questionnaire results are interesting but cannot be used for diagnostic purposes and were not compared with other test results.

### Auditory Attention Switching

As predicted, for both groups of children, the ability to detect the target syllable (see Figure 2: hit rate) was significantly better at the expected epoch compared with that at the

### Table 1. Details of the clinically normed tests that were used to identify the presence of an auditory processing disorder in the study.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Skill</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal processing</td>
<td>Temporal resolution</td>
<td>Gap detection in noise</td>
</tr>
<tr>
<td>Binaural processing</td>
<td>Temporal ordering</td>
<td>FPT</td>
</tr>
<tr>
<td></td>
<td>Binaural integration</td>
<td>DDT</td>
</tr>
<tr>
<td>Speech perception in noise</td>
<td>Speech recognition in presence of spatially separated noise</td>
<td>LiSN–S (high-cue SRT condition)</td>
</tr>
</tbody>
</table>

**Note.** FPT = Frequency/Pitch Pattern Test; DDT = Dichotic Digits Test; MLD = masking level difference; LiSN–S = Listening in Spatialized Noise—Sentences; SRT = speech reception threshold.

### Table 2. The psychoacoustic tests with brief descriptions of the procedure.

<table>
<thead>
<tr>
<th>Skill</th>
<th>Task</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auditory sequential stream segregation</td>
<td>ABA_ paradigm (van Noorden, 1975)</td>
<td>Two pure tones (A and B) were presented in a sequence at a sufficiently high rate using a single-interval, two-alternative-forced-choice paradigm. The frequency separation between tones was varied until the listener could no longer perceive the sequence as a single stream to measure his or her temporal coherence boundary (Bregman, 1994).</td>
</tr>
<tr>
<td>Localization</td>
<td>Speech localization in presence of competing speech (Best, Carlile, Kopčo, &amp; van Schaik, 2011; Kopčo, Best, &amp; Carlile, 2010)</td>
<td>The target speech syllable was presented in one of the seven possible locations in the horizontal plane against a background of two competing talkers. The task of the participants was to point their nose to the perceived location of the target.</td>
</tr>
<tr>
<td>Temporal envelope processing (SAM)</td>
<td>Modulation detection (Rocheron et al., 2002)</td>
<td>Sinusoidal amplitude modulation detection task at a low (4-Hz) and high (128-Hz) modulation rate using an AXB paradigm. We varied the modulation index at a constant modulation frequency to determine the modulation detection thresholds.</td>
</tr>
<tr>
<td>TFS processing</td>
<td>TFS1 and TFS–LF tests (Sek &amp; Moore, 2012)</td>
<td>The TFS1 and TFS–LF tests were used to examine TFS perception for high and low frequencies, respectively. Both tasks involved the use of a two-alternative-forced-choice paradigm.</td>
</tr>
<tr>
<td>Frequency discrimination</td>
<td>Brief tone frequency discrimination (Thompson, Cranford, &amp; Hoyer, 1999)</td>
<td>Frequency discrimination thresholds were examined for short-duration (100-ms) pure tones at 100 and 1000 Hz.</td>
</tr>
</tbody>
</table>

**Note.** SAM = sinusoidal amplitude modulation; TFS = temporal fine structure; LF = low-frequency.
unexpected epochs. When the target appeared at unexpected epochs, the hit rate first decreased significantly and then increased progressively over time. To estimate the predicted time at which the participants would be able to recover their sensitivity to the target, hit rates were extrapolated across the unexpected epochs. For the control group, the expected epoch hit rate was 0.82 ± 0.01, and the regression \( y = 0.098 \times x + 0.26 \), adjusted \( R^2 = .93 \) predicted a recovery to 0.851 ± 0.1 by 2.7 ± 0.1 s (see Figure 2). On the other hand, the extrapolation of hit rates for the LDN group \( y = 0.045 \times x + 0.14 \), adjusted \( R^2 = .88 \) indicated that they would recover their hit rate by 7.9 ± 0.6 s. Thus, on the basis of these findings, the LDN group took a significantly longer time \( (p < .01) \) to reorient their attention to the targets occurring at the unexpected epochs and subsequently to recover their hit rates compared with the controls. These results are consistent with our earlier study in which we reported longer attention reorientation time for a subset of children with listening difficulties in noise (Dhamani et al., 2013). Such a deficit in the ability to switch and rapidly reorient attention may lead to a difficulty in monitoring incoming information from multiple relevant sources and may thus partly explain the listening difficulties reported by the children in noisy or multitalker environments.

The comparison of false-alarm rates between the two groups indicated significantly higher false-alarm rate for the LDN group (0.34 ± 0.02 vs. 0.16 ± 0.02) at the expected epoch (see Figure 3). The LDN group also showed significantly higher overall false-alarm rates (combined across the five epochs) than the control group (0.33 ± 0.02 vs. 0.19 ± 0.02). These findings suggest poor ability to inhibit responses in the LDN group. Poor inhibitory control in the LDN group may also affect their ability to voluntarily inhibit the allocation of attention to irrelevant stimuli in a noisy environment and lead to increased distractibility, adding to listening difficulties.

Overall, the results indicate poor attention switching and inhibitory control in the LDN group compared with the control group. Previous studies have also shown a link between attention switching and inhibitory control ability (Barrouillet & Camos, 2001; Berti & Schröger, 2003; Fillmore, Milich, & Lorch, 2009; Lépine, Bernardin, & Barrouillet, 2005; Luna, Garver, Urban, Lazar, & Sweeney, 2004; Redick, Calvo, Gay, & Engle, 2011). Both these abilities have been suggested to predominantly involve top-down processing (Coull, Vidal, Nazarian, & Macar, 2004; Dhamani et al., 2013; Li, Huang, Constable, & Sinha, 2006), which may indicate a possible top-down (central) information processing deficit in the children with reported listening in noise difficulties.

**Sustained Attention and Memory**

There were no significant differences on the sustained attention task between the groups. This was expected, as participants with diagnoses of attention-deficit/hyperactivity disorder or attention deficit disorder were not included in the study.

The *Clinical Evaluation of Language Fundamentals, Fourth Edition* (Semel et al., 2003) is a widely used clinical tool for examining working memory used by speech-language pathologists and comes with suitable norms allowing for
the assessment of individual performance. In the current study, auditory memory showed significant group differences, \( F(1, 33) = 11.35, p = .002 \), such that the LDN group had lower scores. Planned comparisons showed that the forward digit span (\( p = .014 \)) and backward digit span (\( p = .009 \)) scores were significantly poorer for the LDN group. This is supported by a recent study in which auditory memory was shown to correlate with speech perception in children (Kraus et al., 2012).

Although the LDN group had overall lower scores, on an individual level, only one child scored below 2 SDs of the mean. In a study investigating the cognitive and behavior abilities in children with memory concerns (Alloway, Gathercole, Kirkwood, & Elliott, 2009), it was suggested that anyone with scores 1.28 SDs below the mean has mild deficit, with lower scores indicating greater degrees of severity. By this standard, none of the remaining participants would be diagnosed clinically as having memory deficits (on the basis of the 2 SDs below the norm criterion commonly employed by audiologists).

**Auditory Processing Deficits**

As discussed above, a large battery of clinically normed (see Table 1) and research-based (see Table 2) tests were used to (a) clinically identify participants in the LDN group and (b) test a number of other auditory functions that may discriminate the LDN group from the control group and/or discriminate subgroups within the LDN group. The data were analyzed in two ways. A group comparison was first undertaken with age as a continuous variable for all auditory processing tasks. Second, individual performance was compared with available norms.

The group analysis showed similar performances for most tasks with the exceptions of frequency pattern, MLD, and 4-Hz sinusoidal amplitude modulation (SAM) tasks (see Tables 3 and 4). Thresholds for the LDN group were significantly worse than the control group, \( F(1, 33) = 6.47, p = .02 \). FPT is often noted in literature to be poorer in populations with listening in noise concerns (Sharma, Purdy, & Kelly, 2009). Similarly, but to lesser extent, binaural unmasking or MLD has been noted to be poorer in at least some children with early history of otitis media with effusion and/or listening in noise concerns (Sharma et al., 2002). The differences between the groups in our study for 4-Hz SAM are interesting. Previously, some studies have shown phase locking, as measured by the low modulation rates of 4 Hz, to be poorer in children with dyslexia (Lorenzi, Dumont, & Fullgrabe, 2000; Rocheron et al., 2002). The LDN group had more children with greater reported difficulties with their reading.

When individual performance was compared with norms, the performance of all participants in the control group was within the expected range for all the clinically normed auditory processing disorder (APD) tasks (FPT, DDT, gap detection in noise, LiSN–S test, and MLD). Most of the LDN group also showed age-appropriate performance on most clinical APD tasks (DDT, MLD, and gap detection in noise). All LDN children showed MLD performance within expected norms, although performance was significantly worse overall than the control group. Five children in the LDN group performed very poorly on the FPT and had performance scores more than 3 SDs below the age-based norm (Kelly, 2007). On the basis of the American Academy of Audiology (2010) guidelines, as these children have scores worse than 2 SDs, they will be diagnosed as having an APD.

In a recent study (Peter et al., 2014), norms for children 7–12 years of age have been made available for the 4-Hz SAM task. Only two children in the LDN group demonstrated thresholds within 2 SDs of the norm. This raises the question of the criterion, and if the scores are within 2 SDs, should this be diagnostic of an auditory processing deficit? This point has been discussed in some depth (Dillon et al., 2012). In the absence of clear guidelines, for the purposes of this article, the scores of 2 SDs for the 4-Hz SAM task have been regarded as a concern and indicative of an auditory processing deficit.

Previous research has suggested that modulations are relevant for speech perception in noise (Chi, Gao, Guyton, Ru, & Shamma, 1999), and at least two children showed scores on 4 Hz to be higher than expected. Interestingly, one of these children had significantly low memory thresholds as well (as stated earlier). In another study, it was reported that children with specific language impairment as a group had poorer auditory memory (backward and forward digit span test) as well as 4 Hz, consistent with the current study (Ziegler et al., 2011). The children had reported reading difficulties, and although language was not assessed in the current study, there is a high comorbidity reported between reading and language disorders (Sharma et al., 2009). Notably, other work has highlighted the importance of the 4-Hz temporal processing test in the population with dyslexia and specific language impairment (Rocheron et al., 2002; Ziegler, Pech-Georgel, George, Alario, & Lorenzi, 2005).

**Is Poor Performance on FPT Because of Poor Frequency Discrimination (FD)?**

FPT requires skills such as FD, temporal ordering, and linguistic labelling (Musiek, 2002; Musiek & Pinheiro, 1987). Poor FPT performance could be due to deficit in one of more of these skills (Musiek, 2002; Musiek & Pinheiro, 1987). All children who participated were invited for further testing to assess FD; however, only a subset consented to participate in this additional task. This group included five participants each in the control group (mean age = 11.4 years, \( SD = 0.49 \)) and the LDN group with normal auditory processing scores (mean age = 11.25 years, \( SD = 2.17 \)). In addition, all five LDN children who had performed poorly on FPT and met the clinical criterion for APD agreed to participate (mean age = 13.47 years, \( SD = 2.02 \)). The performance of the children across the three groups on FPT for both ears was significantly different, \( F(2, 11) = 56.04, p < .001 \), such that the APD group was significantly poorer than the control group (\( p < .001 \)) and the LDN group (\( p < .001 \)).
To examine the role of duration, frequency (FD) was assessed for 100-Hz and 1000-Hz pure tones in three different ways: (a) using a relatively short 100-ms duration stimulus with a 300-ms interstimulus interval (ISI), (b) using a longer stimulus duration stimulus (500 ms) with the same ISI (300 ms), and (c) using a longer ISI (500 ms) but a short stimulus duration (100 ms).

Figure 4 shows the individual performance by all children on the FD task on a log scale for Condition 1 (100-ms stimulus, 300-ms ISI). As the figure shows, the FD scores within the APD group were much higher than for the other two groups, particularly for the 1000-Hz stimulus. Figure 5 shows the mean (and 95% confidence interval) of the three groups on the three conditions. Only for 1000 Hz, APD group performed poorer irrespective of duration or ISI. As the number of children is just five in each group, nonparametric analysis was undertaken to compare the APD group with that of control group for the three conditions. Mann–Whitney U tests showed that for each condition for 1000 Hz, APD performed significantly poorer than the control group ($p = .009$). Similarly for 100 Hz, the APD group was poorer irrespective of the stimulus parameters ($p = .028$).

Table 3. Means (± standard deviations) as well as the significance stated for all the normed clinical tests of auditory processing used in the current study.

<table>
<thead>
<tr>
<th>Test</th>
<th>Subtest</th>
<th>Control M (± SD)</th>
<th>LDN M (± SD)</th>
<th>Statistical difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPT (%)</td>
<td>Right ear</td>
<td>92.0 (± 8.1)</td>
<td>84.4 (± 17.8)</td>
<td>$F(1, 33) = 4.57, p = .04^a$</td>
</tr>
<tr>
<td></td>
<td>Left ear</td>
<td>94.4 (± 6.6)</td>
<td>93.2 (± 16.9)</td>
<td></td>
</tr>
<tr>
<td>DDT (%)</td>
<td>Right ear</td>
<td>98.1 (± 3.5)</td>
<td>94.1 (± 6.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left ear</td>
<td>94.6 (± 7.8)</td>
<td>91.6 (± 6.2)</td>
<td></td>
</tr>
<tr>
<td>LISN–S (dB)</td>
<td>Spatial advantage</td>
<td>0.03 (± 0.99)</td>
<td>0.06 (± 2.44)</td>
<td>$F(1, 33) = 1.43, p = .24$</td>
</tr>
<tr>
<td></td>
<td>Talker advantage</td>
<td>0.26 (± 0.56)</td>
<td>0.06 (± 0.95)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low cue</td>
<td>0.15 (± 0.74)</td>
<td>0.06 (± 0.77)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High cue</td>
<td>−0.08 (± 0.85)</td>
<td>−0.47 (± 1.56)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total advantage</td>
<td>0.03 (± 0.70)</td>
<td>−0.27 (± 1.27)</td>
<td></td>
</tr>
<tr>
<td>MLD (dB)</td>
<td>Control</td>
<td>11.3 (± 3.52)</td>
<td>13.4 (± 2.50)</td>
<td>$F(1, 33) = 4.49, p = .04^a$</td>
</tr>
<tr>
<td>Gap detection in noise (ms)</td>
<td>Control</td>
<td>2.9 (± 0.97)</td>
<td>2.8 (± 0.99)</td>
<td>$F(1, 33) = 2.64, p = .61$</td>
</tr>
</tbody>
</table>

Note. LDN = listening difficulty in noise.

$^a$Shows where there was a significant difference between the groups.

To examine the role of duration, frequency (FD) was assessed for 100-Hz and 1000-Hz pure tones in three different ways: (a) using a relatively short 100-ms duration stimulus with a 300-ms interstimulus interval (ISI), (b) using a longer stimulus duration stimulus (500 ms) with the same ISI (300 ms), and (c) using a longer ISI (500 ms) but a short stimulus duration (100 ms).

Figure 4 shows the individual performance by all children on the FD task on a log scale for Condition 1 (100-ms stimulus, 300-ms ISI). As the figure shows, the FD scores within the APD group were much higher than for the other two groups, particularly for the 1000-Hz stimulus. Figure 5 shows the mean (and 95% confidence interval) of the three groups on the three conditions. Only for 1000 Hz, APD group performed poorer irrespective of duration or ISI. As the number of children is just five in each group, nonparametric analysis was undertaken to compare the APD group with that of control group for the three conditions. Mann–Whitney U tests showed that for each condition for 1000 Hz, APD performed significantly poorer than the control group ($p = .009$). Similarly for 100 Hz, the APD group was poorer irrespective of the stimulus parameters ($p = .028$).

Table 4. Means (± standard deviations) as well as the significance stated for all the psychoacoustic tests of auditory processing used in the current study.

<table>
<thead>
<tr>
<th>Skill</th>
<th>Test</th>
<th>Group M (± SD)</th>
<th>Statistical difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAM</td>
<td>4 Hz</td>
<td>Control: −24.5 (± 2.0)</td>
<td>$F(1, 33) = 6.47, p = .02^a$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LDN: −22.3 (± 2.9)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>128 Hz</td>
<td>Control: −21.1 (± 2.7)</td>
<td>Planned comparison 4 Hz: $p = .02^a$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LDN: −20.0 (± 1.8)</td>
<td></td>
</tr>
<tr>
<td>TFS</td>
<td>HF</td>
<td>Control: 29.1 (± 20.1)</td>
<td>$F(1, 33) = 1.10, p = .30$</td>
</tr>
<tr>
<td></td>
<td>LF</td>
<td>Control: 27.6 (± 10.5)</td>
<td></td>
</tr>
<tr>
<td>Localization (angle errors)</td>
<td>Lateral</td>
<td>Control: 13.0 (± 2.6)</td>
<td>$F(1, 33) = 4.02, p = .05$</td>
</tr>
<tr>
<td></td>
<td>Polar</td>
<td>Control: 16.3 (± 5.3)</td>
<td></td>
</tr>
<tr>
<td>Stream segregation</td>
<td>Temporal coherence boundary</td>
<td>Control: 69.5 (± 31.1)</td>
<td>$F(1, 33) = 0.302, p = .59$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LDN: 63.8 (± 27.9)</td>
<td></td>
</tr>
</tbody>
</table>

Note. HF = high-frequency.

$^a$Shows where there was a significant difference between the groups.
Earlier studies conducted on children with dyslexia and specific language impairment have also shown difficulty in discrimination of rapidly presented short duration sounds (Hari & Renvall, 2001; Martino, Espesser, Rey, & Habib, 2001; Reed, 1989; Tallal, Miller, & Fitch, 1993; Wright et al., 1997). These studies used shorter duration sounds (<75 ms) than the current study (100 ms) with a variable ISI and found poor performance on temporal sequencing and discrimination tasks at short ISIs (<305 ms). In the current study, the duration was longer, and the ISI was fixed at 300 ms, but the FD scores were still poorer in the current APD group. Increasing the duration from 100 to 500 ms somewhat improved the percept for both pure tones, especially for 100 Hz (see Figure 5). It is, therefore, possible that the poor performance of the children with APD on this task is associated with their frequency resolution ability at short durations, although this is still slightly longer (100 ms) than suggested by the previous literature (<40 ms). FD performance did not seem to vary with change in ISI.

Another noteworthy aspect of these data is that the FD threshold at 1000 Hz for the APD group (at 100-ms duration) was about 41 Hz, whereas the FPT uses frequencies of 1100 and 880 Hz (thus, a difference of 120 Hz). Consequently, the difficulty on FPT is not likely to be just limited to FD. Furthermore, there were differences in the relative thresholds for the two frequencies for the APD group as well (see Figure 5). Also, there is no reason for 100 Hz to improve with increase in duration but not 1000 Hz. The stimulus durations used in the FD test here were slightly shorter (100 ms) or really long (500 ms) than that used in the FPT (150 ms)—a smaller step size may have been more useful.

The poor performance of the APD group on the FD task may be associated with a frequency resolution deficit associated with either a cochlear or central auditory dysfunction (Badri, Siegel, & Wright, 2011; B. C. J. Moore, 1996; Strelcyk & Dau, 2009). The difficulty appears to be a spectral difficulty or at least an interaction of spectral–temporal deficits, as a longer stimulus duration did improve the thresholds for the APD group for 100 Hz. Consequently, the current results do not simply conform to the rapid temporal processing deficit theory (Tallal, 1980). In a recent review article (Kleindienst & Musiek, 2011), five different studies (different researchers and, hence, different sets of children)
were cited showing significantly poorer FD in groups of children with specific language impairment, but none of these studies explored whether changes in temporal cues affected the thresholds. Hence, the FD results are interesting and require further evaluation. A systematic study of FD needs to be undertaken exploring the effects of both the duration across frequencies in populations with LDN or at least APD.

**General Discussion**

**Attention, Memory, Auditory Processing, and Listening in Noise**

Speech perception or listening in noise is an interaction between attention, memory, and auditory processing. To be clear, in this context, the term noise refers to other masking sounds that will almost always include other talkers and therefore involve informational as well as energetic masking (Kidd et al., 2008). Studies using functional magnetic resonance imaging have reported evidence of involvement of common cortical areas, such as the left ventral and dorsal prefrontal cortex for speech perception in noise and working memory (Salat, Kaye, & Janowsky, 2002; Wong, Ettinger, Sheppard, Gunasekera, & Dhar, 2010; Wong et al., 2009). It has also been suggested that the prefrontal cortex may be responsible for inhibiting the processing of competing sounds (Wong et al., 2010).

The current study aimed to investigate whether there were one or more factors that were affected in participants with normal hearing sensitivity reporting listening difficulties in noise. A recent review article (Hämäläinen, Salminen, & Leppänen, 2013) has systematically looked at the incidence of FD deficits in about 30 research articles in dyslexia population, and about half showed significant differences. Similarly, in another study, it was summarized that the children with dyslexia and language impairment have deficits in speech perception in noise. Thus, there is evidence from various sources that populations with normal hearing sensitivity have deficits in listening in noise and FD. There is evidence mounting that speech perception in noise is linked to processing at brain-stem (Chandrasekaran, Hornickel, Skoe, Nicol, & Kraus, 2009) and cortical (Warrier, Johnson, Hayes, Nicol, & Kraus, 2004) levels, but the underlying mechanism is still not clear.

Listening difficulties in noise may result from a number of deficits, such as attention disorders, language, as well as hearing loss (Sharma et al., 2009). Similarly, listening difficulties could also imply a number of different things, for instance, difficulty following instructions, understanding instructions, and/or distraction. Because of the ambiguity of terminology and medley of factors involved, studies, such as the ones reported here—in which batteries of individual factors are assessed using objective performance measures—are necessary to better diagnose and plan an intervention.

The inclusion of the questionnaire in this study was useful to identify the individual participant’s concern(s). The questionnaire showed that the children with listening difficulties and their parents had concerns with their listening and reading more than the control group. The behavioral assessments showed that, as a group, the LDN group performed poorly on auditory attention switching, some auditory processing (FPT, MLD, 4-Hz SAM), and auditory memory tasks. The diversity of results should, therefore, not be that surprising considering that a range of processing deficits could produce a similar symptomatic presentation (i.e., LDN).

Most studies report group data, and, hence, in the current study, it was useful to look at the group data for comparison purposes. Having said that, published performance norms were available for most of auditory processing and memory tasks, and these were used to determine individual performance. The group differences were interesting, but many of those differences could not be categorized as “deficits” on the basis of the currently accepted norms. All the children in the control group performed within the expected age-appropriate norms, whereas the LDN group showed some individual differences. Indeed, a central difficulty in studying such deficits is the likely heterogeneity of cause.

It is not immediately obvious why only a subset of the LDN group (i.e., the APD group) showed additional deficits in their frequency resolution. Individual variations in auditory processing skills have been reported in the previous literature with children with specific language impairment (Bishop & McArthur, 2005) and dyslexia (Messaoud-Galusi, Hazan, & Rosen, 2011). In both these studies, only a small proportion showed poor performance. Bishop & McArthur (2005) went on to cite that only about one third had difficulty on basic FD, which is similar to proportion in the current study (5/21). Thus, in the current study, most children with LDN had skills similar to the control group whereas only a subset of children (APD) had a specific deficit on FD as reported in the previous research.

In the present study, attention switching was found to be slower in the LDN group compared with the control group. There is a need to establish clinical norms for this task so as to be able to determine the performance of an individual child against normal population performance as a potential diagnostic measure. Considering that all children with reported listening in noise may be at risk of attention switching deficits raises the question as to whether the attention switching task should be included within the APD test battery. The current data suggest that listening in noise deficits are an interaction of auditory processing and attention processes, and, hence, attention processes should be part of the test battery. The current research is consistent with other work also suggesting that the test battery should include cognitive measures such as attention and memory (D. R. Moore et al., 2010; Sharma et al., 2009). However, more work is needed before the current paradigm of attention switching could be considered part of the routine clinical set up. For instance, contribution of spatial location of different talkers is not understood in listeners with LDN. There is a discussion on modality specificity in the APD literature (Cacace & McFarland, 2005), and, hence, future studies need to evaluate whether LDN participants have a global attention switching deficit or a modality specific disorder.
A listening difficulty in the presence of background noise as a consequence of poorer working memory, auditory processing, and/or attention deficits may be explained on the basis of the information degradation hypothesis (Pichora-Fuller, 2003a, 2003b). In the context of listening in noise, a deficit in any of the factors may mean that the task of listening to a single talker would engage most of the capacity to cope with the deficit, and the remaining capacity would then be inadequate to simultaneously monitor other inputs (Rudner et al., 2012). In the context of current findings, LDN listeners have a deficit in attention switching that is not related to their pure tone sensitivity but very likely reflects a central processing problem. LDN listeners have much greater switching inertia compared with normal listeners, that is, they take significantly longer to reorientate their auditory attention when there is a sharp change in the listening environment (as occurs when the conversation shifts from one talker to the next in a dynamic conversation), and consequently all their resources are spent in trying to keep up. The increased cost of switching attention between talkers and presumably the increased effort of listening consequently leads to the reported complaints of listening deficits in “noise.”

These results do emphasize the need to include the tests of attention and FD in the test battery. In older listeners, it has been reported that FD deficits might make it harder to separate speech from background noise (Gordon-Salant & Fitzgibbons, 1997; Schneider & Pichora-Fuller, 2000), and this then compounds the deficits in attention switching (Tun, O’Kane, & Wingfield, 2002). Could this be what is occurring for at least a subset of the current population? It is possible that the frequency resolution deficits observed in the APD group are independent of their attention switching and inhibitory control ability.

On the basis of these results, it would appear that there are two subsets of children with reported listening concerns in noise: one with attention switching deficits and another with attention switching as well as FD deficits. The results strongly recommend the inclusion of these tests in the current test battery.

**Conclusion**

The present study assessed attention, memory, and auditory processing skills in school-age children with persistent listening difficulties in background noise. The results of the attention shifting task indicate that children in the LDN group had attention switching and inhibitory control deficits. Some of these children had additional deficits in their frequency resolution skills. On the basis of these results, it would be reasonable to suggest that, when assessing people with listening difficulties in noise, assessment of attention switching and frequency resolution should be included in the clinical test battery.

**Acknowledgments**

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**References**


Chandrasekaran, B., Hornickel, J., Skoe, E., Nicol, T., & Kraus, N. (2009). Context-dependent encoding in the human auditory...


Appendix (p. 1 of 2)

Questionnaire

Name of participant: ________________________________

DOB [date of birth] of the participant: ________________________________

Gender Female □ Male □

Handedness Right □ Left □ Ambidextrous □

Did your child receive ESL [English as a second language] support at school? Yes □ No □

Address ____________________________________________

Phone ____________________________________________

E-mail ____________________________________________

Does your child have or ever had concerns about your hearing, listening, or reading? Yes □ No □

Does anybody in the immediate family have a hearing concern? Yes □ No □

If yes, how are they related to the child?

__________________________________________________________

Have the school or work place colleagues raised any concerns about your child’s hearing or listening? Yes □ No □

If yes, what are their concerns?

__________________________________________________________
Appendix (p. 2 of 2)

Questionnaire

Does your child have any history of earache, infections, or grommets?  Yes □ No □
If yes, since when and how many episodes? Please provide as much information as possible:
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________

Does anybody in the family have reading difficulties?  Yes □ No □
If yes, how are they related to the child?
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________

Has your child repeated any school year?  Yes □ No □
If yes, which year, and could you provide more information?
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________

Are there any other medical or health concerns?
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________

Are there any other issues you have observed regarding your child’s concentration, memory, or attention?
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________

Up to this point has your child received any assistance or therapy for any of your concerns?  Yes □ No □
If yes, what kind of assistance or therapy?
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________
__________________________________________________________________________________________________________________________________

Please rate the child’s ability based on your observation for the following:
Rating scale:  1 = Very Good  2 = Good  3 = Average  4 = Poor  5 = Very Poor
Hearingability:  1  2  3  4  5
Listening ability:  1  2  3  4  5
Reading ability:  1  2  3  4  5
Listening in noise:  1  2  3  4  5

Name
Signature
Date