

NEUROPHYSIOLOGICAL BASES OF FREQUENCY DISCRIMINATION IN
CHILDREN WITH AUDITORY PROCESSING DISORDER
OR SPECIFIC LANGUAGE IMPAIRMENT

by

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Abstract

NEUROPHYSIOLOGICAL BASES OF FREQUENCY DISCRIMINATION IN 10-12 YEAR-
OLD CHILDREN WITH AUDITORY PROCESSING DISORDER
OR SPECIFIC LANGUAGE IMPAIRMENT

by

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The purpose of this study was to determine if 10-12 year old children with Auditory Processing Disorder (APD) or Specific Language Impairment (SLI) could discriminate three different frequency changes behaviorally and electrophysiologically. Behavioral frequency discrimination and event-related potentials were examined using a 1000Hz pure tone base frequency. Typically developing children and children with APD or SLI differed in their detection of frequency changes: behavioral results were below chance level and the MMN amplitude was smaller in the impaired population. Slight differences between children with APD and children with SLI were also found that might shed light on the controversy regarding the deficits underlying pediatric APD, either a disorder in itself, or a symptom of a higher information processing deficit.

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I dedicate this work to the memory of my niece, Lisa Rota, who died in December 2011 at the age of 10.

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Overview

Auditory processing disorder (APD) has become a common diagnosis for children who have difficulty in school or who struggle with language processing. Pediatric APD refers to atypical auditory skills development in the absence of a documented peripheral hearing loss. These auditory performance deficits are often associated with other higher order processing difficulties, such as specific language impairment (SLI), reading disabilities (RD), autism spectrum disorder (ASD), or attention deficit hyperactivity disorder (ADHD) (e.g., Stefanatos & DeMarco, 2012). Because of this co-morbidity, some researchers suggest that APD is the result of a higher order developmental dysfunction (e.g., Bishop, 2007), and the distinction between APD and SLI or other associated disorders is controversial (e.g., Rosen, 2005). Children who are still developing and maturing atypically usually show a variety of symptoms and their listening difficulty is rarely isolated. Therefore, it is difficult to determine based on clinical observations whether APD is a disorder in itself, or if it is merely a symptom of a higher order information processing deficit. Often, depending on whether the child sees an audiologist or a speech language pathologist first, the diagnosis can be APD or SLI (Ferguson, Hall, Riley, & Moore, 2010).

The main gap in the understanding of pediatric APD is that *pure forms* of APD (Dawes & Bishop, 2009) have not been studied independently from language and other related cognitive impairments. Thus, it is necessary to study children who have APD with and without language impairment. If APD is a specific perceptual auditory disorder (Cacace & McFarland, 2005), confounding stimulus and task factors such as attention, working memory, and language have to be controlled. In addition, nonlinguistic auditory processing needs to be assessed before conscious attention or linguistic processes are likely to exert a strong influence. Auditory evoked

potentials (AEPs), recorded at the level of the scalp using surface electrodes, provide a very effective way of examining the auditory system at the pre-attentional level (see Naatanen, Paavilainen, Rinne, and Alho [2007] for a review). However, the use of speech stimuli to investigate auditory processing is problematic because speech sound processing involves both detection of a signal and higher order brain processes (Hickok & Poeppel, 2000). Thus, deficits in speech sound processing can stem from either a perceptual disorder or a more specific speech/language deficit.

Consequently, in the study of a perceptual auditory dysfunction such as APD, it is essential to have some studies using non-verbal stimuli. Several aspects of the physical attribute of sounds can be studied (i.e., phase, frequency, duration, and intensity). Because of the earlier work of Paula Tallal and her colleagues, who showed that children with learning problems had difficulty processing rapid auditory signals (e.g., Tallal, Miller, & Fitch, 1993), temporal aspects of perception have been emphasized in the study of atypical auditory perception in children (see Bishop [2007] for a review). However, more recent studies have shown that spectral processing of speech and frequency processing of non-speech are also important (e.g., Hill, Hogben, & Bishop, 2005). Spectral cues are particularly important for speech intelligibility in children with hearing losses (e.g., Nie, Barco, & Zeng, 2006) and in the processing of non-speech sounds by children with SLI (e.g., McArthur & Bishop, 2005). There is evidence for impairment of frequency discrimination (FD) in atypically developing children (e.g., Kleindienst & Musiek, 2011), contrary to claims by Tallal and her colleagues (Tallal et al., 1993). FD is a basic auditory task that can measure non-verbal auditory processing abilities, before sounds are processed linguistically or at the conscious level. Therefore, FD could be used to study auditory perceptual

abilities in typically and atypically developing children and may clarify the distinction between pediatric APD, a perceptual auditory deficit, and SLI, a higher order deficit.

The Mismatch Negativity (MMN) is the cortical potential of choice in the study of sound discrimination because it can be elicited in response to small changes in the stimulus physical properties such as frequency (e.g., Sams, Paavilainen, Alho, & Naatanen, 1985). The MMN is the enhanced negativity that appears in adults around 100-250ms after the deviant in an odd-ball type of stimulus presentation, where a deviant stimulus is presented infrequently. In children the MMN is influenced by maturational effects. Overall the MMN latency decreases with age at the rate of 11ms/year between 4 and 10yrs for tones (Shafer, Morr, Kreuzer, & Kurtzberg, 2000) and by 25ms/year between 4 and 7yrs for speech (Shafer, Yu, & Datta, 2010). The amplitude, although significantly smaller in adults than children, does not show the same developmental changes. Rate of presentation is also of great importance, especially in children where significant differences in the MMN morphology can be seen (Sussman, Steinschneider, Gumenyuk, Grushko, & Lawson, 2008). An SOA of about 600ms seems, therefore, optimal in the recordings of MMN in 10-12 year-old children (Sussman et al., 2008).

Differences in the MMN in response to pure tones have already been noted in children with developmental delays such as children with SLI (e.g., Ahmmed, Clarke, & Adams, 2008). However, in the Ahmmed, Clarke, and Adams (2008) study, the participants were not tested for APD and results might have been difficult to interpret because the atypically developing children might have had SLI with or without APD. One original aspect of the present study is that the sample population is defined using auditory processing and language testing to permit analysis of frequency discrimination abilities in children with APD or SLI.

In addition to the MMN, the obligatory P1 and Ta amplitude and latency will be reported. The cortical P1-N1-P2-N2 is a sequence of peaks elicited by a sound or by a change in a continuous sound. This sequence of peaks is present in typical adults between 50ms and 250ms after the onset of the stimulus: the latency of the first positive peak P1 is around 50ms, followed by a negative peak N1 around 80ms, another positive peak P2 around 180ms, and finally a negative peak around 200/250ms. In children P1 shifts in latency with age and the N1 component emerges around 9 years of age (e.g., Ponton, Eggermont, Khosla, Kwong, & Don, 2002 and Sussman et al., 2008), thus, P1 can be used to rule out general maturational delays of the obligatory P1-N1-P2 complex in atypically developing children. Bishop and McArthur (2005) have shown that these obligatory responses were sometimes delayed in children with SLI, but that they were also similar to that of younger typically developing children. The authors concluded that these findings might suggest a possible maturational delay of the P1-N1-P2 complex in children with SLI. When measured at the temporal sites, this obligatory response is called the T-Complex which includes the Na, Ta and Tb peaks; these peaks are fairly mature by 5 years of age (e.g. Tonnquist-Uhlen, 1996). However, Ta is attenuated in amplitude in children with SLI (Shafer, Schwartz, & Martin, 2011) in response to speech stimuli; the present study examines whether this finding holds for non-speech stimuli.

Overall, the goal was to study three groups of atypically developing children, one group with *APD only*, one with *SLI only*, and another with both APD and SLI. The hypothesis was that children with *APD only* and children with *SLI only* would differ. FD was expected to be affected in children with APD at a behavioral level and at the neurophysiological level, indexed by the MMN. The prediction was that poor behavioral performances on FD tasks would be the consequence of poor processing of small frequency changes at an early neurophysiological level

for children with APD. In contrast, for the children with *SLI only* the prediction was that the poor behavioral FD would not be seen at the level indexed by the MMN. Rather, children with *SLI only* would show good FD at the level indexed by the MMN. It was presumed that children with SLI and not APD may have poor behavioral performance due to their language deficit and poor labeling ability, but not because of neurophysiological differences at the level of the MMN. Indeed, in the case of children with APD, poor behavioral FD was expected to be a consequence of poor neural discrimination in the auditory cortex and indexed by reduced or absent MMN in response to small frequency changes. However, in the case of children with *SLI only*, poor behavioral FD was expected to reflect poor language skills not targeted by the MMN, the main electrophysiological component of the study. Thus, the MMN in response to nonverbal frequency changes in children with *SLI only* was expected to be similar to that of typically developing children.

Another important aspect of the current study was to combine behavioral and non-behavioral measures using the same stimuli, because poor FD performances on the behavioral tasks might have been associated with atypical brain detection of small changes in frequency or might have been affected by more global information processing difficulties involving language or attention. Therefore, it is only by combining both behavioral and non-behavioral measures that interpretation of the underlying brain processes of poor behavioral FD performances can be achieved.

Auditory Processing Disorder (APD)

Pediatric APD is a communication deficit often associated with difficulty learning in school or problems interacting in everyday life. Children with APD usually experience difficulty listening in noisy environments and difficulty following directions in the absence of a peripheral

hearing loss or neurological deficits. Other symptoms include poor sound localization, impaired dichotic listening and difficulties with sound patterns recognition (American Speech-Language Hearing Association [ASHA], 2005; American Academy of Audiology [AAA], 2010).

At this time there is no gold standard test battery to diagnose APD; there is still no consensus regarding which test battery can best identify children with APD and no objective measure, such as oto-acoustic emissions or electrophysiology, to characterize this deficit. So, most audiologists base their conclusions on behavioral assessments that include speech and non-speech tasks. As a result, a multidisciplinary approach is recommended to establish the child's developmental profile (ASHA, 2005; Dawes & Bishop, 2009) and to determine if language, cognitive, or attention deficits are also present. When the deficits center on auditory skills, rather than on language skills or other factors, children are said to have APD if they score two standard deviations or more below the mean on at least two behavioral central auditory tests (American Academy of Audiology, 2010).

The test most commonly used to assess pediatric APD in the United States is the SCAN, Test of Auditory Processing Disorders. There are two versions of the SCAN for children: the SCAN-C (Keith, 2000) and the newer SCAN-3:C (Keith, 2009). These tests are composed of different subtests: filtered words, auditory figure ground, competing words, and competing sentences, with a newly added gap detection screening to the latest version. Other commonly used tests involve behavioral assessment of non-speech sound processing: the Pitch Pattern Sequence Test (Pinheiro & Musiek, 1985), the Duration Pattern Sequence Test (Musiek, Baran, & Pinheiro, 1990), the Gap In Noise Test (Musiek, Shinn, Jirsa, Bamiou, Baran, & Zaida, 2005), the Random Gap Detection Test (Keith, 2000), and the Masking Level Difference test (Schoeny & Talbott, 1994). Auditory speech processing is also tested by presenting syllables, words or

sentences dichotically (where a different stimulus is presented to each ear simultaneously). These tests include the Staggered Spondaic Word Test (SSW, Katz, 1986) and the Dichotic Digits Test (Musiek, 1983). Occasionally measures of APD also include electrophysiology, such as the Middle Latency Response (MLR, e.g., Musiek, Bellis, & Chermak, 2005), the P300, also known as the P3 (e.g. Jirsa, 1992), or the BioMAP (Kraus, Nicol, & Zerker, 2005). Because auditory evoked potentials (AEPs) are time consuming, expensive, and not always modality specific, they are rarely used clinically.

In the literature and in clinical practice the term *auditory processing* can be used to refer to different types of processing: such as the processing of nonverbal auditory stimuli or the processing of auditory linguistic stimuli. It is important to distinguish between the two, because auditory inputs that are processed by the auditory cortex might involve different central nervous system pathways than auditory inputs that are processed later by the language areas of the brain (Richard, 2001). The obligatory components P1 and N1 index fairly early the detection and encoding of acoustic information that is then processed at a higher level, at the level of P3 and N4 present in adults between 250ms and 1000ms after the onset of the stimulus (see Stapells [2002] for a review of the AEPs).

A large part of the controversy regarding APD comes from the use of the term *auditory processing* which for some authors refers to the detection of an auditory input at the level of the auditory pathways and for other authors refers to the processing from auditory input through linguistic levels of processing auditory information. Furthermore, because of its comorbidity with other developmental delays (i.e., specific language impairment or attention deficit disorder), APD in children has rarely been studied in isolation. As a result, the question of whether pediatric APD is an auditory modality specific difficulty or a broader processing problem

remains. Two views dominate the debate. One model considers APD to be a higher order deficit (e.g., Bishop, 2007), and the other describes APD as a modality specific perceptual disorder (e.g., Cacace & McFarland, 2005). Determining which model is correct is important because these different models suggest different diagnoses and treatment approaches. If poor auditory skills are part of higher order language impairment, a linguistic approach to treatment would be more appropriate (Chermak & Musiek, 1997; Kelly, 1999; Lucker, 2008). In contrast, if these auditory symptoms reflect an auditory only disorder, then auditory-based treatment strategies such as auditory training would be justified (Tallal, 1993; Scientific Learning Corporation, 2008; Halliday, Taylor, Edmondson-Jones, & Moore, 2008; Tremblay, Shanin, Picton, & Ross, 2009). However, there is no evidence at this time that auditory interventions lead to improved functions. Some clinicians argue that for intervention to be successful, children with APD who are treated using an auditory approach should also receive intervention targeting language and academic goals (Fey, Richard, Geffner, Kamhi, Medwetsky, Paul, Ross-Swain, Wallach, Frymark, & Schooling, 2011).

Specific Language Impairment (SLI)

Specific language impairment is characterized by difficulty acquiring language as expected in the absence of known neurological disorders, cognitive, emotional, or sensory deficits. This linguistic disorder can affect phonology, morphology, syntax, semantics, and discourse; it can be expressive or receptive. These language deficits can be associated with auditory perception/processing deficits, reduced vocabulary, working memory, attention, and executive function deficits (Schwartz, 2009). Some clinical symptoms of SLI are similar to symptoms of APD (e.g., difficulty following directions or poor comprehension of spoken messages) and children with SLI have profiles of performance and reported disabilities similar to

children with APD (Ferguson, Hall, Riley, & Moore, 2010). Furthermore, two lines of research suggest that deficit in auditory processing (Tallal et al., 1993) and deficit in auditory perception (Leonard, 1989) may explain at least some of the language deficit seen in children with SLI.

Thus, the differentiation between children with SLI and children with APD is not always clear in clinical practice or in research.

In the last decades, electrophysiology has increasingly been used to study children with SLI (e.g., Bishop, Hardiman, Uwer, & von Suchodoletz, 2007; Schwartz, 2009) and non-verbal auditory processing deficits have been reported (e.g., Korpilahti & Lang, 1994). Despite numerous studies on non-verbal auditory processing in atypically developing children, results are often mixed and contradictory because the children included in these studies had SLI, but were not tested for APD (e.g., McArthur & Bishop, 2005).

Frequency discrimination

Frequency discrimination (FD) is the perceptual ability to detect the difference in pitch between two sounds, usually two pure tones. Several methods are used to measure FD abilities and some of these involve the subject to behaviorally respond, whereas others do not. When tested behaviorally FD involves attention and the ability to label and store the information in memory, as well as the ability to resolve pitch difference. Thus, poor behavioral FD can be the result of poor processing on a number of different levels. AEPs can be used to indicate if the difference in pitch can be detected by the brain without requiring a behavioral response. AEPs also provide excellent temporal resolution of sound detection along the auditory pathway and can be used to examine whether differences in FD are related to poor frequency resolution or slow processing.

Behavioral measures of FD in children. Behaviorally, typically developing children can detect very small frequency changes; studies reported Δf thresholds in children at 1% of the base frequency at 1000Hz (Moore, Ferguson, Halliday, & Riley, 2008), at 0.7% of the base frequency at 500 Hz and at 0.5% of the base frequency at 3000Hz (Rota-Donahue, 2010). In the atypically developing population findings of elevated Δf thresholds were reported in children with SLI where Δf was between 8.5% and 15.5 % of the 1000Hz base frequency (Nickisch & Massinger, 2009). However, in another study, results seen in children with SLI overlapped with the ranges of results in the control group; Δf in children with SLI was between 1.5% and 7.6 % of the 1000Hz base frequency and in the control group Δf ranged between 1% and 2.5% (Hill, Hogben, & Bishop, 2005).

Electrophysiological measures of FD in children. The detection of small frequency changes by the auditory central nervous system can be indexed by the P1-N1-P2 or the MMN. The Acoustic Change Complex (ACC), the obligatory P1-N1-P2 cortical AEP elicited by an acoustic change (Martin & Boothroyd, 1999), was found in typically developing children at 0.7% of the base frequency at 500Hz and at 0.5 % of the base frequency at 3000Hz (Rota-Donahue, 2010). The MMN can also be elicited in typically developing children by small frequency changes, 2%, 5% and 10% changes from the base frequency (Ahmmed, Clarke, & Adams, 2008).

One of the earliest electrophysiological studies to report anomalies in frequency processing of non-speech sounds in the cortex showed that, when compared to typically developing peers, children with SLI had longer latency and smaller amplitude N2 to a 500 Hz and a 553 Hz pure tone (Korpilahti & Lang, 1994). Absent or delayed latency of the T-complex in response to a 500Hz tone, and increased latencies and decreased amplitude of all the peaks of the P1-N1-P2 complex were also noted (e.g., Tonquist-Uhlen, 1996; Bishop & Mc Arthur,

2005). In addition, atypical MMN responses, using a 700Hz standard and a 750 Hz deviant (Rinker, Kohls, Richter, Maas, Schulz, & Schecker, 2007), were reported. However, these findings contradict other findings where no difference was found between children with SLI and their typically developing peers (e.g., Tomblin, Abbas, Records, & Brenneman, 1995; Uwer, Albrecht, & vonSuchodoletz, 2002).

A recent study showed some differences in the MMN responses between children with SLI and age-matched peers, in response to small frequency changes (2%, 5% and 10%) from the 1000Hz base frequency (Ahmmed et al., 2008). The children with SLI were divided into a subgroup that performed well on gap detection and a subgroup that performed poorly on gap detection. An odd-ball task was designed using a 1000Hz pure tone as the standard and was presented at two rates: a 200ms ISI and a 400ms ISI. Results showed that the P1 and N2 peaks were present for all stimulus contrasts, at both ISIs, for the control group and the group of children with SLI. MMN results were also similar in the control group and in the group of children with SLI: the two larger frequency changes elicited an MMN, and a positive mismatch response was elicited with the longer ISI, 400ms. However, at shorter ISI, results seem to indicate that children with SLI, who also performed well on the gap detection test, had a stronger MMN response than either the control group or the group of children with SLI who performed poorly on the gap detection test. Generally, children who had the worst MMN morphology were the children with poor gap detection abilities. The presence or absence of APD in these children may have been responsible for the difference in some of the findings, but because the participants were not tested for APD, interpretation of the results is uncertain.

Purpose of the study

To date, studies of frequency discrimination in children have either used non-modality specific components (e.g., the P3 in Jirsa [1992]), behavioral only measures (e.g., Moore et al., 2008) or sample populations of children with SLI who were not tested for APD (e.g., Ahmmed et al., 2008). Consequently, results are unclear and confusing because either both electrophysiological and behavioral results were affected by language or attention deficits, or the sample population tested was not well defined. To avoid confounding attention and language, the present study analyzed the obligatory P1-N1-P2, the T-complex responses and the MMN, AEPs components obtained before more complex level of processing takes place. Furthermore, to define the population of participants more clearly, the current study included testing or screening for hearing, attention, non-verbal cognitive abilities, language, and auditory processing abilities. In addition, to examine the perception of frequency changes and to clarify the interpretation of the results, this study examined behavioral and non-behavioral FD using the same stimuli for the behavioral and the electrophysiological part of the experiment.

The purpose of this study was to determine if there were differences between FD processing in children with or without APD or SLI and whether children with *APD only* differed from children with *SLI only* on a nonverbal auditory task. The goal was also to determine if there was a correlation between FD abilities and auditory processing or language test scores. To do so, FD was studied using a 1000Hz pure tone and three frequency changes that were within the frequency discrimination abilities of typically developing (TD) children. The first frequency change (between 1000Hz and 1020Hz) was 2% of the base frequency, which is slightly above the reported Δf threshold of children with good FD (Moore et al., 2008). The second deviant was 5% of the base frequency, which is above the reported Δf threshold of good performers but still

below the reported Δf threshold of children with poor FD abilities (Moore et al., 2008). The last frequency change was 15% of the base frequency, which is above the reported Δf threshold of children with poor frequency discrimination (or $> 10\%$ of the base frequency).

The prediction was that typically developing children would perform within normal limits on FD behaviorally and electrophysiologically but that children with APD would not (some children with APD were also expected to have SLI). For children with *SLI only*, the prediction was that they would show FD abilities electrophysiologically comparable to the typically developing peers, but poor behavioral FD results because of their language deficit and poor labeling ability. Results were expected to support the notion that pediatric APD is an auditory specific perceptual deficit often associated with, but independent from language or other higher order processing deficits.

METHOD

Participants

Thirty children between 10 years and 12 years 11 months participated in the study: thirteen typically developing (TD) children, six males and seven females, and seventeen children with APD or SLI, ten males and seven females. All participants had normal hearing at 500Hz, 1000Hz, 2000Hz and 4000Hz with thresholds better or equal to 20dBHL for both ears. In addition, they were healthy with no known neurological deficits, English was their first language and they had no known ADHD or ADD.

The other criteria were nonverbal intelligence, language and auditory processing abilities. All participants had nonverbal intelligence scores within normal limits, with nonverbal IQ > 85 on the Test of Nonverbal Intelligence-3 (TONI-3: Brown, Sherbenou, & Johnsen, 1997). The differences between typically and atypically developing children were in their language and auditory processing skills. The five main subtests of the Clinical Evaluation of Language Fundamentals – 4 (CELF-4) (Semel, Wiig, & Secord, 2004) were given to each participant: Concepts and Following Directions, Word Classes-Receptive, Recalling Sentences, Formulated Sentences, and Word Classes-Expressive. To test for auditory processing the SCAN-3:C (Keith, 2009) was also administered to all participants, this test included five subtests: Gap Detection, Auditory Figure Ground (S/N ratio +8dB), Filtered Words, Competing Words and Competing Sentences.

For inclusion in the TD group, participants performed no more than one standard deviation below the mean on the SCAN-3:C and on the CELF-4, their composite score and core language score were greater than 85. For inclusion in the APD group children performed more than one standard deviation below the mean on the SCAN-3:C composite or -1SD or more below

the mean on at least one subtests of three of the five main subtests of the SCAN-3:C (Gap Detection, Auditory Figure Ground and Competing Words). Finally, for inclusion in the SLI group, children performed more than one standard deviation below the mean on the core language score of the CELF-4 or 1 SD or more below the mean on at least two of the five subtests of the CELF-4.

Table 1

Summary of tests scores for the TD group and the APD or SLI group

	TD (<i>n</i> = 13)				APD or SLI (<i>n</i> = 17)			
	<i>M</i>	<i>SD</i>	<i>SE</i>	Range	<i>M</i>	<i>SD</i>	<i>SE</i>	Range
Age, months	137	14	4	120-155	139	12	3	120-155
CELF-4 Core	114	14	4	94-134	84	18	4	54-115
CELF-4	109	13	4	93-131	82	15	4	58-109
Receptive CELF- 4	115	14	4	95-134	84	17	4	57-112
Expressive SCAN-3	104	10	3	89-123	93	12	3	65-113
Composite TONI-3	116	17	5	93-150	100	8	2	82-115
Quotient								

The groups were as follows: thirteen children who were typically developing (TD), four children with *APD only* (APD), four children with *SLI only* (SLI), and nine children with both APD and SLI (*BOTH*). The groups and standard scores on the CELF-4, the SCAN-3:C and the TONI-3 for each participant are presented in table A in the appendix. A summary of the test scores is given in Table 1; more details regarding the APD or SLI group are given in Tables A and B in the appendix.

Stimuli

The behavioral and electrophysiological tasks used four pure tones. The duration of each pure tone was 150ms, with a rise time of 10 ms and a fall time of 10 ms. The base frequency or standard was 1000Hz and the other three tones were: 1020Hz (2% higher than the base frequency), 1050Hz (5% higher than the base frequency), and 1150Hz (15% higher than the base frequency). The tones were presented at 70 dB SPL bilaterally, using earphones, with an ISI of 500ms, or an SOA of 650 ms.

Procedure

Some children attended two sessions of two-hours, but most children and their caretaker chose to attend a four-hour session with a long break (most had lunch at that time). The parent/guardian and the child signed permission forms: a consent form and an assent form (see appendix C). During the first portion of the session, the child completed a hearing screening, the TONI-3, the CELF-4, the SCAN-3:C and the two behavioral tasks; during the second portion of the session the electrophysiological testing was performed. Breaks were given between tests and between runs.

Electrophysiology. For the electrophysiology part of the study an oddball task was used. The base frequency pure tone was 1000Hz and the three deviant tones were 1020Hz, 1050Hz and 1150Hz. A trigger was placed at the onset of each tone, the tones were presented at 70 dB SPL using insert earphones, the sound duration was 150ms and the SOA was 650ms. The stimuli were presented using an oddball paradigm where the standard 1000Hz appeared 85% of the time and the deviant appeared 15% of the time. There were 200 random presentations of the deviant stimuli; the three different magnitudes of frequency changes were presented separately. These three presentation blocks were divided in four runs, for a total of twelve runs. The conditions

were randomized. The event related potentials were measured with standard EEG recording techniques by placing a 32-electrode cap on the participant's scalp. Other electrodes were placed on the mastoids, and on the nose for reference. Electrodes were used to record horizontal and vertical eye movements. Impedance of each electrode did not exceed 10k Ω for any electrode. Responses from the electrodes were digitized at a sampling rate of 500Hz (0.05 – 200Hz bandpass) and amplified. Data were collected and stored for analysis using Neuroscan SCAN 4.3. After recording, the epoch (-100 to 650ms) was baseline corrected and data were processed by artifact rejection ($\pm 100 \mu\text{V}$), filtering (1 to 30 Hz, 12 dB /octave), and averaging by subject and condition.

During testing, the participants were seated in a comfortable chair in a sound-attenuated and electrically-shielded room. The auditory evoked potentials were recorded using the Neuroscan system while subjects were watching a silent video (close-captioned) of their choice. Participants were asked to ignore the sounds and pay attention to the video. For each block, the recording lasted about 15 minutes; breaks were provided as needed between runs.

Behavioral tasks. There were two behavioral tasks: one simple two alternative forced-choice (AFC) procedure and an oddball task. Before each behavioral task children performed a short practice run with feedback to ensure that they had understood the instructions. For the AFC task, the tones were presented in pairs, and children were asked if the two tones were the same or different. Participants clicked 1 on the keyboard if the tones were the same, and clicked on 2 on the keyboard if the tones were different. Stimuli were controlled and presented using E-Prime 2.0 (Psychology Software Tools, 2010). There were 20 randomized presentations of two different tones for each of the three frequency changes and 60 presentations of pairs with no difference, for a total of 120 trials. For the oddball behavioral experiment, participants were asked to click

on the space bar each time they detected a deviant in a chain of 1000Hz standard tones. The probability of the deviant was 15% and there were 20 random presentations of each deviant. Stimuli were presented with an SOA of 650 ms, using E-Prime 2.0.

Data reduction

Electrophysiological data. For electrophysiological data, the amplitude and peak latency of the AEP components were determined visually on the grand average waveforms, at the electrode site of greatest S/N ratio.

The main component of interest was the MMN, obtained by subtracting the average waveform of the standard stimulus from the average waveform of the deviant stimulus. To determine the presence or absence of the MMN, the noise in the window was averaged. If the MMN was statistically greater than the noise, it was considered to be present. The MMN was computed using the Neuroscan 4.3 software for the three magnitudes of frequency change. Data were analyzed for the three frequency changes for the four groups of participants.

The obligatory response was analyzed using the grand mean waveform of the 1000Hz standard in terms of amplitude and latencies at FCz for P1 and at the temporal sites for Na, Ta and Tb. Data were also analyzed for the four groups of participants.

Behavioral data. Percentages of correct responses were calculated for each frequency change magnitude. For the odd ball task, responses between 200ms and 1000ms after the deviant were considered hits. For the two behavioral tasks, > 50% hit rate was considered significantly above chance level (Yost, 2007). The sensitivity index d' was also calculated for each participant for both behavioral experiments. Results are reported for each experiment separately and are given for the four groups of participants for each of the three frequency changes.

Correlations. Correlations were used to determine if the behavioral and electrophysiological results were related to auditory processing and language abilities as measured by the SCAN-3:C and on the CELF 4. Correlation coefficients were also used to determine whether there was an association between behavioral performances and the amplitude of the MMN.

Specific predictions

MMN. The three frequency changes (2%, 5% and 15% of the base frequency) were expected to elicit a significant MMN response in TD children (as already reported by Ahmmed et al. [2008] who found that 2% change in the base frequency could elicit an MMN in TD children). In addition, although not yet reported in the pediatric population, the greatest frequency change was expected to elicit a larger response than the smallest frequency change as already seen in adults (Sams et al., 1985). The MMN should be reduced or absent in children with APD for the smallest frequency change, supporting the main hypothesis that poor auditory perceptual abilities of children with APD could be measured by FD at the level of the MMN, before more complex types of processing take place. In contrast, the children with *SLI only* were expected to have typical MMN responses to all frequency changes.

Obligatory AEP components. P1 was expected to be similar for all children. To confirm that prediction P1's amplitude and latency was analyzed for the four groups of participants, because past studies have shown some conflicting reports regarding P1 in children with atypical development, SLI in particular, (see Bishop [2007] for review).

When recorded at the temporal site, the morphology of the obligatory components, the Ta of the T complex, was expected to be attenuated in children with SLI, as already reported by Shafer, Schwartz, and Martin (2011) in response to syllables and words.

Behavioral tasks. The three frequency changes were expected to elicit a 50% or greater score of correct response for the two behavioral experiments, because the behavioral Δf threshold was reported in previous studies to be around 1% of the base frequency at 1000Hz in children with good FD ability (e.g., Moore et al., 2008). Thus, it was presumed that TD children would easily discriminate frequency changes greater than 1% of the base frequency. However, in children with APD, FD was expected to be poor: above chance level only for the largest frequency change (15% of the base frequency), but not for the other two frequency changes (2% and 5% of the base frequency). Poor FD performers had behavioral thresholds of 10% of the base frequency (Moore et al., 2008). Thus, children with APD were not expected to discriminate between tones with a Δf smaller than 10% of the base frequency, but were expected to be able to discriminate tones when the difference between them was larger ($\geq 10\%$ of the base frequency). In children with *SLI only*, the hypothesis was that they would also show poor behavioral performances, because their language deficit was supposed to affect their ability to label and process sounds. Children with SLI and APD were expected to perform more poorly because in addition to auditory deficits they would also have linguistic deficits compounding the problem of detecting and labeling small frequency changes.

Correlations. The MMN was expected to be a good predictor of behavioral frequency discrimination abilities (e.g., Pakarinen, Takegata, Rinne, Huotilainen, & Naatanen, 2007) for TD children or for children with APD, but not for children with *SLI only*. TD children were expected to have good behavioral frequency discrimination abilities and exhibit significant MMN responses for the three frequency changes. Children with APD were expected to show poor behavioral FD abilities indexed at the level of the brain by weaker (or absent) MMN in response to small frequency changes. However, in children with *SLI only*, poor behavioral FD

was not supposed to result in reduced MMN in response frequency changes because their deficit was not expected to manifest itself at that level.

RESULTS

The population samples were too small to use inferential statistics for group comparisons with the two smallest groups ($n = 4$ for the *APD only* group and $n = 4$ for the *SLI only* group). Thus, the distribution of the core language, receptive language, expressive language, auditory processing and nonverbal intelligence scores are presented in box plots. Graph D in the appendix shows these box plots for the four groups in details. Figure 1 shows the distribution of the standard scores obtained on the CELF-4 core (blue boxes) and the composite of the SCAN-3 (green boxes) for the four groups.

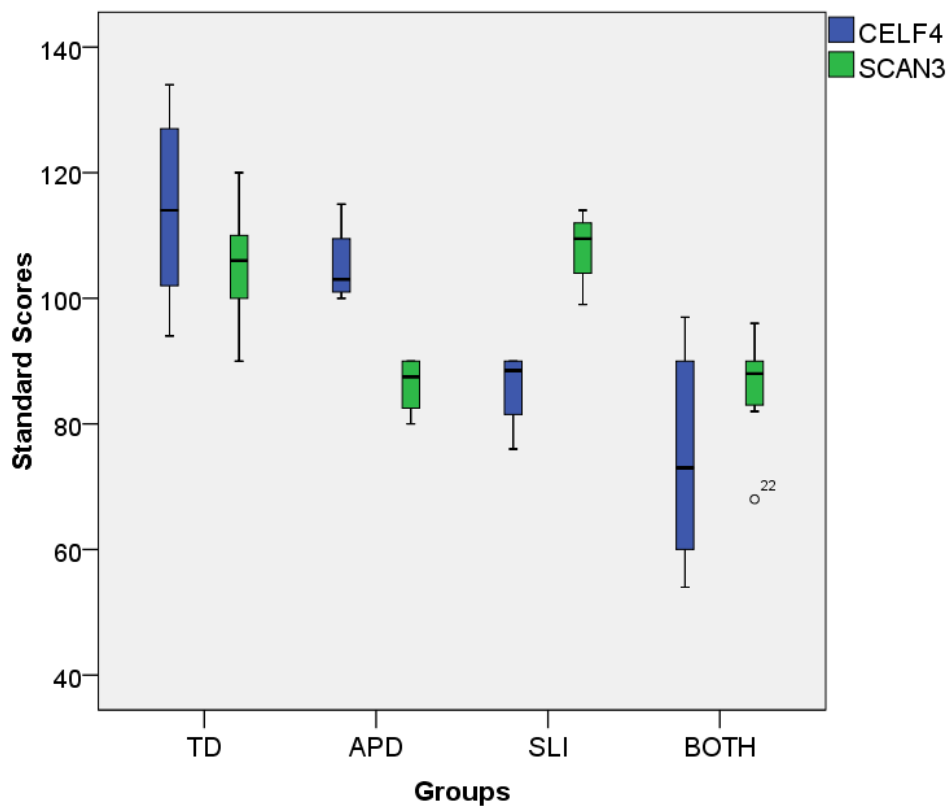


Figure 1: Distribution of standard CELF-4 core scores and the composite of the SCAN-3:C for the four groups of participants.

The distribution of scores revealed that most of the TD children scored above 100 on the CELF-4 and on the SCAN-3. Most of the children with *APD only* scored above 100 on the

CELF-4 but below 100 on the SCAN-3. For the children with *SLI only*, the pattern was reversed, with most children scoring above 100 on the SCAN-3 but below 100 on the CELF-4. The children with both APD and SLI scored below 100 on both the SCAN-3 and the CELF-4.

The Levene test for equality of variance and the Kolmogorov-Smirnov test of normality of the distribution revealed that the variance across groups did not differ and the scores were normally distributed. Once equality of variance and normality of the distribution was established for each group, a two-tailed t-test was used to compare them for each of the dependent variables: Core Language Score, Receptive Language Score, Expressive Language Score, Auditory Processing SCAN-3:C composite score and non-verbal IQ score on the TONI-3. The typically developing children were different from the children with APD or SLI on these standardized measures of language and auditory processing skills (with a significance level < 0.02). Table E in the appendix summarizes the level of significance for the mean difference on these measures between the typically developing children and the other group of children with APD or SLI.

Electrophysiological measures

MMN. The waveforms of the standard and of the three deviants were recorded at each electrode site. The best signal to noise ratio for the deviant tones were observed at electrode site Fz. Waveforms of the standard and of the deviants at Fz are shown in Figure F in the appendix for the four groups of participants (TD, APD, SLI, and BOTH). The three frequency changes, from the largest change on the left to the smallest change on the right, are reported. The standard waveform is represented in blue and the deviant waveforms are in green.

The waveforms of the three deviant tones clearly show an enhanced negativity when compared to the standard waveform for the TD group, the *APD only* group and the *SLI only* group. However, the differences between the standard waveform and the deviant waveforms are

not as pronounced for the group of children with both APD and SLI. Figure 2 shows the waveforms of the deviant tone 1050Hz (5% of the base frequency) and of the standard for the TD group and for the BOTH group (see Figure F in the appendix for more details).

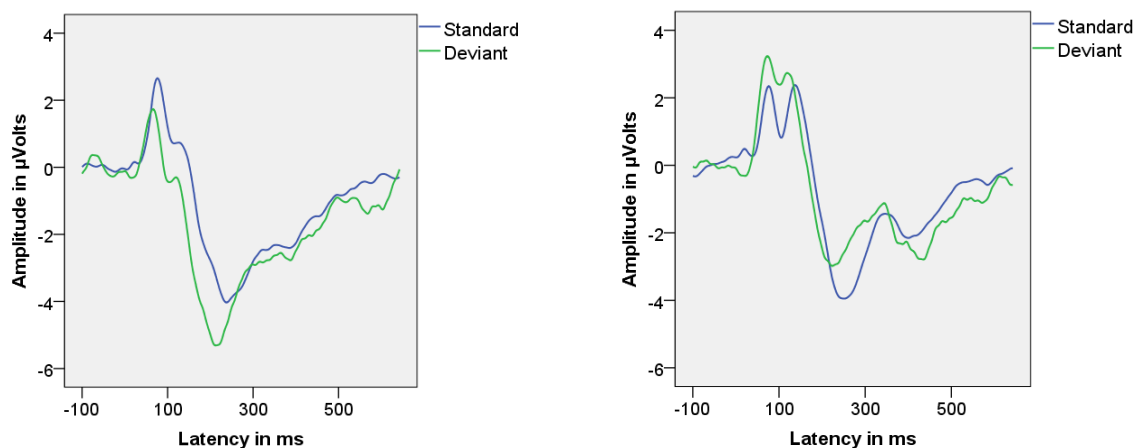


Figure 2: Standard and deviant waveforms for the 5% frequency change for the TD group on the left and for the *BOTH* group on the right.

For each participant and for the groups, the difference waveforms were analyzed in terms of latency and amplitude at electrode site Fz, the site with the best S/N ratio. The peak of the latency and amplitude of the MMN were recorded. The MMN was considered significantly greater than zero if its peak amplitude was greater than the average noise in the window (the average amplitude of the noise was calculated by using the standard deviations from the mean waveform in the window). Most participants showed a negative MMN for the three conditions, two participants in the *BOTH* group showed no MMN (meaning that although negative these MMN amplitudes were not greater than the noise in the window), and one participant in the *BOTH* group showed a positive MMN. The figures below (Figures 3 and 4) show the amplitude of the difference waveforms for the three frequency changes for the TD group. The difference waveforms are labeled as follow: *dif1150* for the 1150Hz difference waveform in blue, *dif1050* for the 1050Hz difference waveform in green and *dif1020* for the 1020Hz difference waveform

in grey. In addition to averaging the MMN difference waveforms for each group, the MMN average amplitude in the window (40ms around the peak) was also calculated for each condition for each group and reported in Table 2.

Table 2

MMN mean average amplitude of the difference waveforms in μ Volts (and SD), for the four groups of participants, for the three frequency changes.

	TD	APD	SLI	BOTH
1150	-2.14 (0.3)	-0.91 (0.2)	-1.61 (0.2)	-0.45 (0.2)
1050	-2.06 (0.8)	-1.12 (1.2)	-1.96 (0.1)	-1.77 (0.2)
1020	-0.80 (0.1)	-1.02 (0.7)	-1.51 (0.2)	0.36 (0.2)

Figure 3 shows the difference waveforms for the three frequency changes for the TD group. The largest frequency changes: 15% of the base frequency and 5% of the base frequency generated the largest difference waveforms. For the 1150Hz and the 1050Hz changes the MMN average amplitude was $-2.14 \mu\text{V}$ ($SD = 0.3$) and $-2.06 \mu\text{V}$ ($SD = 0.8$), respectively. The smallest frequency change, 2% of the base frequency, yielded a smaller difference waveform than the larger frequency changes. For this 1020Hz frequency change, the average amplitude of the difference was $-0.8 \mu\text{V}$ ($SD = 0.1$). As the difference in frequency between the deviant and the standard gets smaller, the MMN amplitude decreases. Results for the APD group and the SLI group are reported in figure G in the appendix. That figure shows the difference waveforms for these two groups of children for the three frequency changes. For the APD group and for the SLI group the difference waveforms show large negative amplitudes for all the frequency changes: with average amplitudes from the largest to the smallest of -0.91 , -1.12 and $-1.02 \mu\text{V}$ for the

APD only group and of -1.61, -1.96 and -1.51 μV for the *SLI only* group, respectively. However, each group of participants is small (four subjects in each).

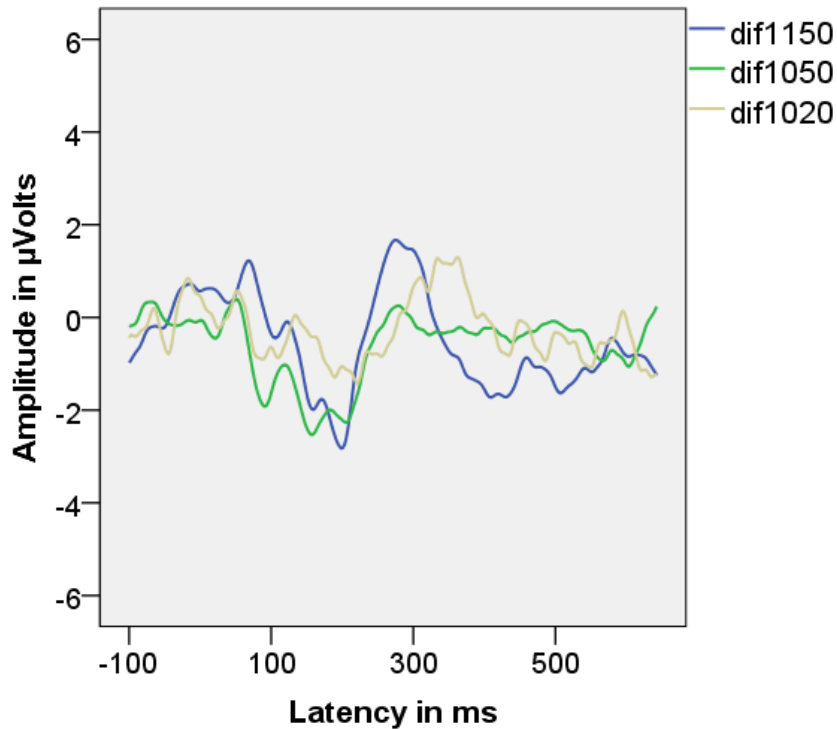


Figure 3: MMN difference waveforms for the TD group for the three frequency changes

In contrast, the *BOTH* group shows reduced MMN amplitudes, especially for the smallest frequency change where the MMN is absent. Figure 4 represents the subtraction waveforms for the *BOTH* group for the three frequency changes, with an average amplitude in the window of -0.45 μV for the 1150Hz frequency change, -1.7 μV for the 1050Hz frequency change, and an average amplitude of 0.36 μV for the 1020Hz frequency change. Differences were found between the MMN amplitude of the TD group and the MMN amplitude of the *BOTH* group for the 1150 Hz change [$t(20) = -19.7, p < .001$] and for the 1020Hz change present [$t(20) = -27.1, p < .001$].

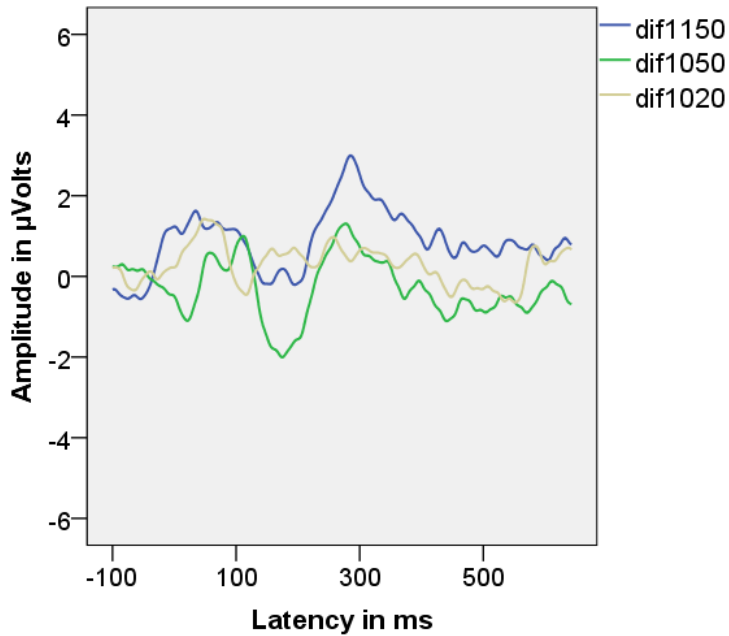


Figure 4: MMN difference waveforms for the *BOTH* group for the three frequency changes

P1. For each participant and for each group, the latencies and amplitudes of the P1-N1-P2 complex were obtained by analyzing the average standard waveforms, only P1 latencies and amplitudes are reported because P1 measures can be used to assess whether the participants in the groups are at the same maturational level, since the peak latency of P1 moves earlier and its peak amplitude declines with increasing age (Ponton., Eggermont, Khosla, Kwong, & Don, 2002).

For all participants the morphology of the P1-N1-P2 in response to the 1000Hz base frequency pure tone was as expected. Figure 5 shows the average waveforms at FCz for each group of participants: the TD group is represented in blue, the APD group in green, the SLI

group in grey, and the *BOTH* group in purple.

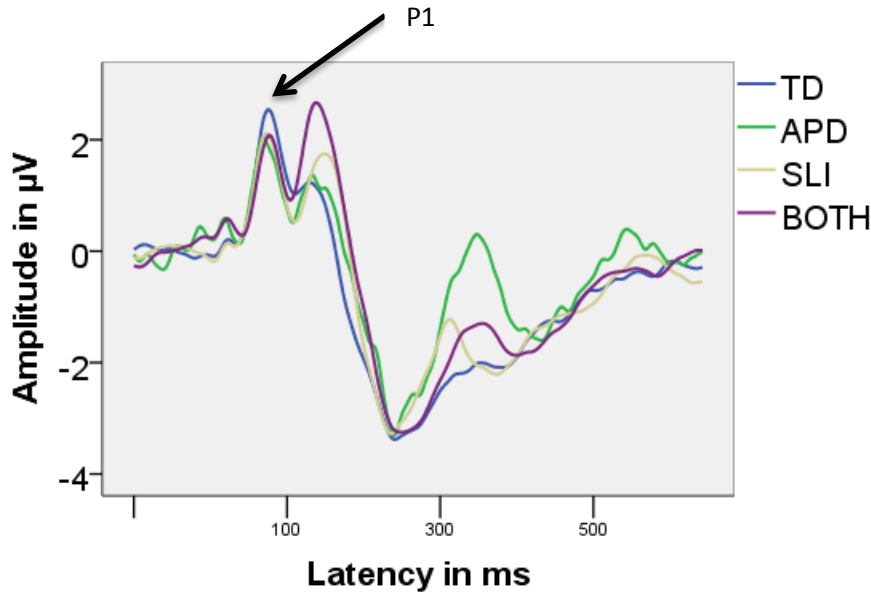


Figure 5: P1-N1-P2 for the average standard waveform at FCZ for the four groups.

The latency and amplitude of P1 was obtained for each participant and for each group at electrode FCz, the electrode site with the largest response. Both the latencies and amplitudes of the P1 peak were nearly identical for the groups. The mean P1 latency was 80 ms for the TD group, 80ms for the APD group, 78ms for the SLI group and 80ms for the *BOTH* group, respectively. The mean P1 amplitude was 2.2µV for the TD group, 1.9µV for the *APD only* group, 2.0µV for the *SLI only* group, and 1.8µV for the *BOTH* group, respectively. Graphs H1 and H2 in the appendix show the box plots representing these findings.

T Complex. The standard waveforms were analyzed at the level on the temporal electrodes T7 and T8 and the three peaks Na, Ta and Tb were measured in terms of latency and amplitude. The amplitude of Ta is the only measure reported here. The amplitude of Ta was found to be significantly smaller at T7 than at T8 for all participants [$t(29) = -2.87, p = .007$]. Ta’s average amplitude for each group of participants is given in Table I in the appendix. Figure 6 shows the waveforms for the standard stimulus recorded at T7 and T8.

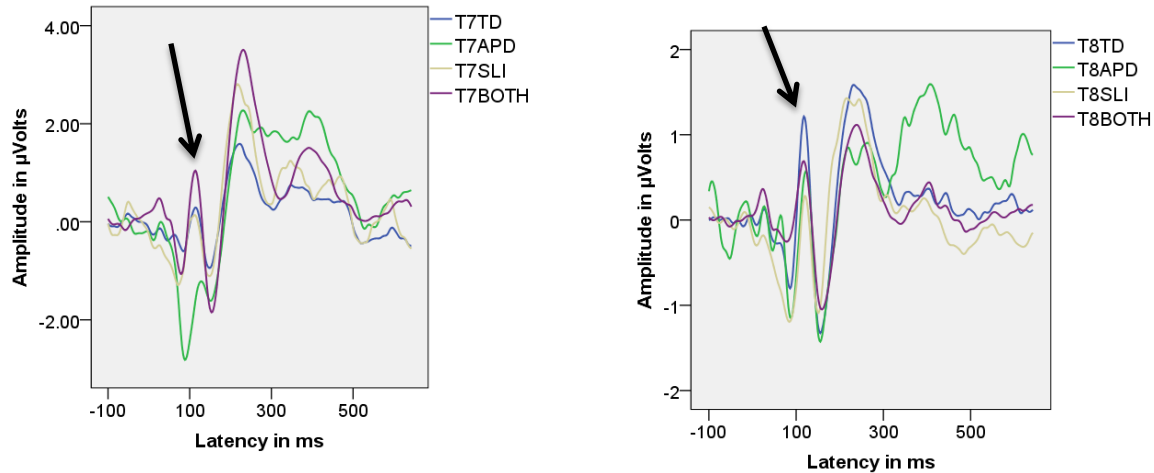


Figure 6: T complex at T7 and T8 for the four groups of participants, Ta marked by black arrow

Overall electrophysiological results showed:

- Strong MMN responses to the three frequency changes for all participants, except for the children in the *BOTH* group.
- P1 similar in all participants
- Ta significantly larger on the right than on the left side of the head

Behavioral results

For the two behavioral tasks: frequency discrimination and odd ball task, percentages of correct responses (hits) for each of the frequency changes were determined (*M* hit rates and *SD* are displayed in Table J in the appendix). In addition to the hit rates, false alarm rates were calculated and the sensitivity index d' was determined for each participants using the formula $d' = z(H) - z(F)$. The bias criterion *c* was also calculated using the formula $c = -1/2 [z(H) + z(F)]$.

Frequency Discrimination Task. Percentages of correct responses were calculated for each frequency change. For all groups, the percentage of correct responses was highest for the largest frequency change (*M* = 90%), less for the medium change (*M* = 75%) and lowest for the smallest change (*M* = 48%).

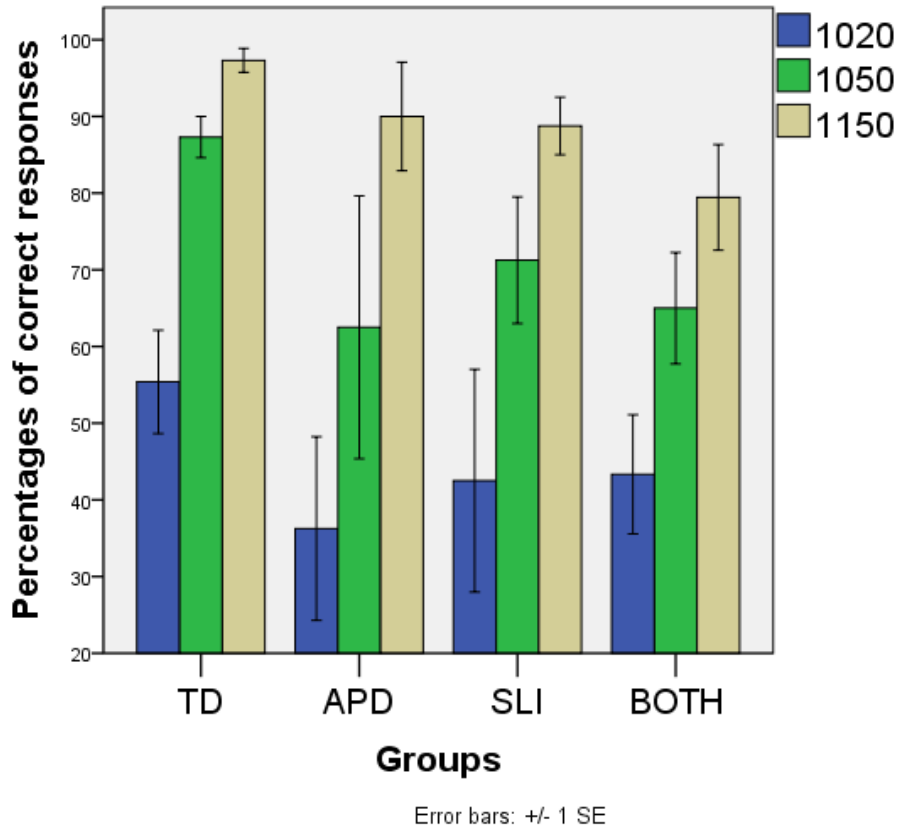


Figure 7: Distribution of percentages of correct responses on the frequency discrimination task for the four groups across the three frequency changes 1020Hz, 1050Hz and 1150Hz.

Figure 7 shows the score distribution for the four groups of participants with the standard error from the mean brackets included. As expected, the TD group performed above chance level for the three frequency changes. Although the children with *SLI only* performed slightly better on average, the APD and SLI children performed similarly. The three groups of atypically developing children performed below chance level for the smallest frequency change (1020Hz represented in blue) and above chance level for the other frequency changes (1050Hz in green and 1150Hz in grey). The group with both SLI and APD performed essentially lower than all the other groups for the three frequency changes.

In addition to hit rates, the sensitivity index and the bias criterion were obtained. For the frequency discrimination task most children showed a bias toward saying *same* ($M_c = 0.44$, $SD = 0.26$) indicating that children were more likely to say that two tones were the same when they did not perceive a difference or when they were not sure of the response. Two children in the *BOTH* group had negative bias criterion and large numbers of false alarms. However, most children were conservative [TD group $M_c = 0.42$ ($SD = 0.22$), children with APD or SLI group $M_c = 0.45$ ($SD = 0.28$): the groups did not differ $t(28) = 0.294$, $p = 0.771$].

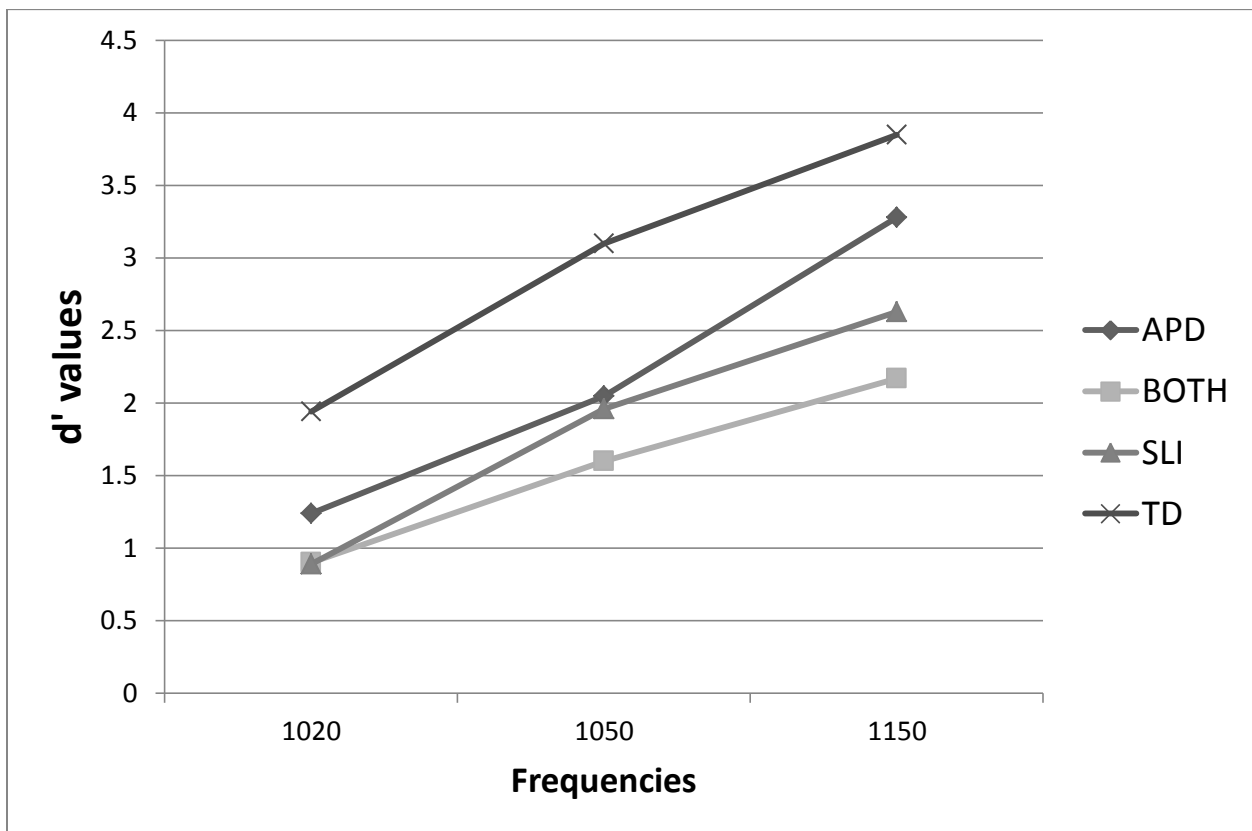


Figure 8: Frequency discrimination d' values for the three frequency changes by groups (the blue horizontal line represents chance level).

Figure 8 shows the values of the sensitivity index d' for the three frequency changes for the four groups of participants. To be above chance level d' has to be greater than 1.0 (Macmillan & Creelman, 2005). For the smallest frequency change, 1020Hz or 2% of the base

frequency, the d' value is greater for the TD group than for any other groups, the mean d' values are below chance level for the *SLI only* and for the *BOTH* groups. For the 1050Hz and the 1150Hz frequency changes, the mean d' values are above chance for all groups. An independent sample t-test was run to compare the mean d' values between the TD and the *BOTH* groups; a significant difference between means was found between the TD group and the *BOTH* group [$t(20) = 3.29, p = 0.004 < 0.025$]. The mean d' values are given for each frequency change for the four groups in Table K1 in the appendix.

Odd ball task. Percentages of correct responses were calculated for each frequency change. For all groups, the percentage of correct responses was greatest for the largest frequency change ($M = 90\%$), lower for the medium change ($M = 75\%$), and lower for the smallest change ($M = 48\%$).

Figure 9 shows the detail of the distribution of scores for the four groups of participants with the standard error from the mean bars included. As expected, the TD group performed above chance level for the three frequency changes. The *APD only* and *SLI only* children performed similarly. The three groups of atypically developing children perform below chance level for the smallest frequency change (1020Hz represented in blue) and above chance level for the other frequency changes (1050Hz in green and 1150Hz in grey).

In terms of bias, all children were equally conservative. Their bias was toward not clicking the space bar instead clicking the space bar when unsure of the response ($M_c = 0.78, SD = 0.42$). All children were conservative [TD group $M_c = 0.61, (SD = 0.33)$, children with APD or SLI group $M_c = 0.92, (SD = 0.46)$; the groups did not differ $t(28) = 0.507, p = 0.483$].

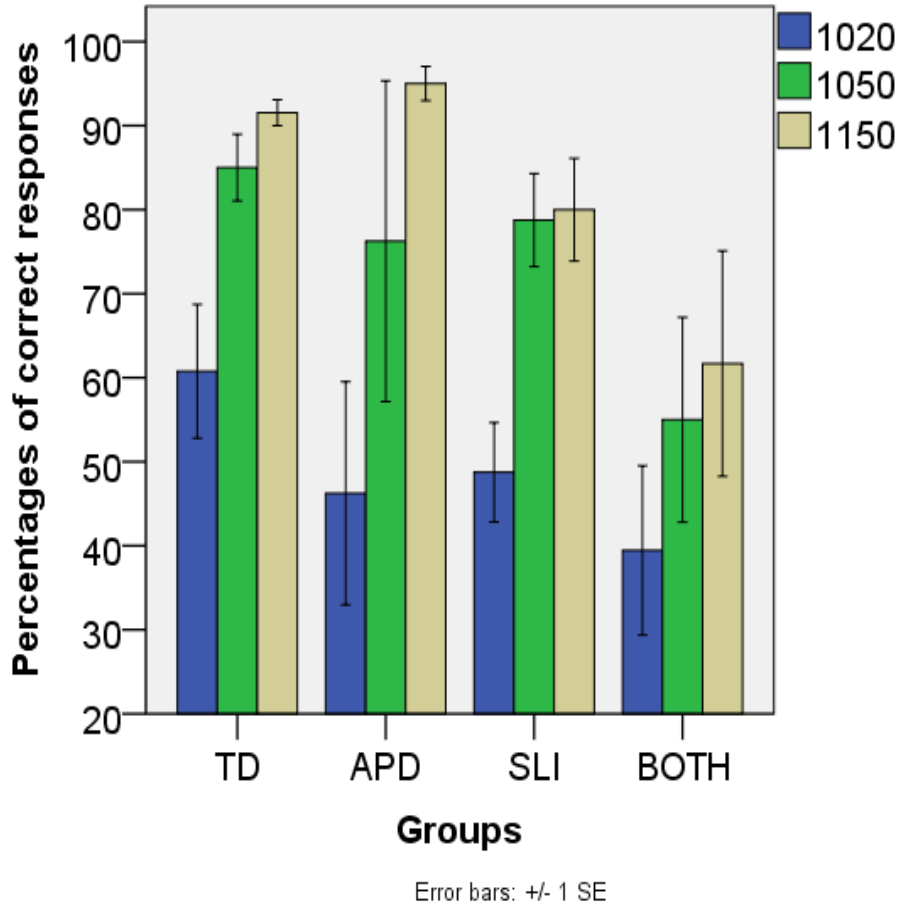


Figure 9: Distribution of percentages of correct responses for the odd ball task for the four groups of participants for the three frequency changes 1020Hz, 1050Hz and 1150Hz.

For the sensitivity index, the mean d' for the four groups of participants was significantly different from zero [$M_{d'} = 2.75, t(29) = 13.94, p < .001$]. The sensitivity index was compared for the TD group and for the clinical group of children with APD or SLI; $M_{d'}$ was significantly larger for the TD group than for the atypically developing group [TD group $M_{d'} = 3.23 (SD = 0.74)$, children with APD or SLI $M_{d'} = 2.39 (SD = 1.18), t(28) = 2.24, p = .033 < .05$]. Children in the TD group were better able to identify the deviant tone in a string of tones than the children with APD or SLI. The distribution of d' scores for the four groups is summarized in Table K2 in

the appendix. The mean d' values for the three frequency changes across groups are shown in Figure 10. Although d' values are larger for the children in the TD group, all d' values are above chance level for all children. An independent sample t-test was run to compare the means of the d' values among the four groups; the only the TD group and the *BOTH* group differed

[$t(20)=2.71, p=0.013 < 0.025$]

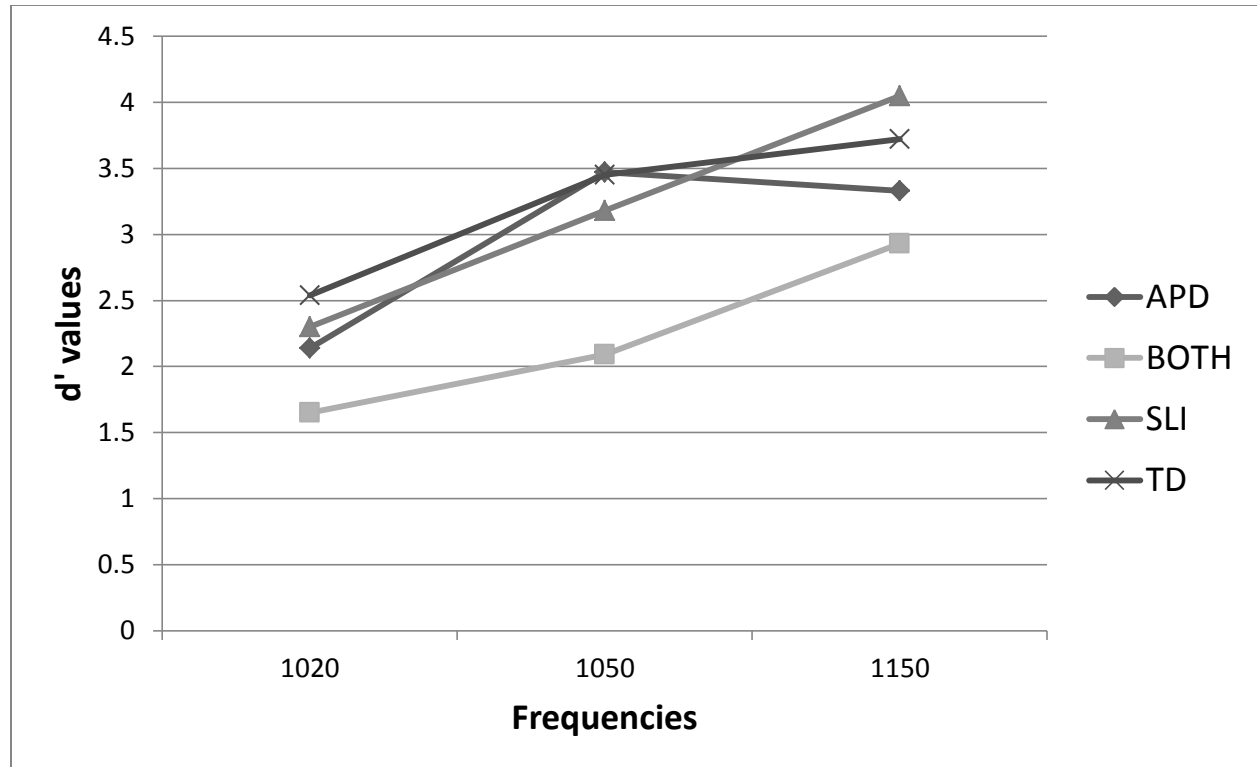


Figure 10: Odd ball task d' values for the three frequency changes for the four groups of participants (the blue line represents chance level).

Overall, behavioral results were as expected. All frequency changes discriminated above chance level by the TD children, but the hit rates was not as good for the atypically developing children (a summary of the mean hit rates and d' for the two behavioral tasks is given in Table J and Tables K1 and K2 in the appendix).

Correlations

The Pearson correlation coefficients were calculated and to determine the strength of the relationship between the independent variables SCAN-3:C and CELF-4 and the dependent variables MMN amplitude and behavioral tasks (frequency discrimination and oddball) hit rates the coefficients of determination were obtained. The correlation coefficients between MMN amplitude and hit rates are also reported. Table L in the appendix summarizes these findings.

Although the MMN response was significantly reduced for the smallest frequency change for the *BOTH* group, no correlation greater than .5 was found between the independent variables SCAN-3:C and CELF-4 and the dependent variable MMN amplitude.

In contrast, some large correlation coefficients ($r > .5$) were obtained between the independent variables SCAN-3:C and CELF-4 and the dependent variables hit rates on the behavioral tasks. As the scores on the SCAN-3:C or the CELF-4 decreased hit rates on the behavioral tasks decreased. However, the effect size of that relationship was not similar in all cases. For the two largest frequency changes, children with lower CELF-4 scores had lower the hit rates on the behavioral tasks for the two largest frequency changes, 15% and 5% of the base frequency. For the FD task, the Pearson coefficients were: $r = .676$ ($p < .001$) for the largest frequency change, and $r = .508$ ($p = .004$) for the median frequency change; the coefficient was small (r around .1) for the smallest frequency change [$r = .179$ ($p = .345$)]. For the oddball task, the results were similar; the Pearson coefficients were $r = .551$ ($p = .002$) for the largest frequency change, and $r = .518$ ($p = .003$) for the median frequency change; the coefficient was smaller (r around .3) for the smallest frequency change [$r = .34$ ($p = .345$)].

The Pearson correlation coefficients were also calculated between SCAN-3:C and the hit rates on the behavioral tasks, medium to large correlations were obtained for the two smallest

frequency changes and smaller coefficients for the largest frequency change. For the FD task, the Pearson coefficients were: $r = .467$ ($p = .009$) for the medium frequency change, and $r = .419$ ($p = .021$) for the smallest frequency change; the coefficient was smaller for the largest frequency change [$r = .304$ ($p = .103$)]. For the oddball task, results were similar; the Pearson coefficients were $r = .422$ ($p = .02$) for the medium frequency change, and $r = .440$ ($p = .015$) for the smallest frequency change; the effect coefficient was smaller for the largest frequency change [$r = .379$ ($p = .039$)].

Overall, significant relationships were found between the SCAN-3:C and CELF-4 and the behavioral tasks hit rates for the three frequency changes. To determine how much of this effect on behavioral results could be explained by results on the SCAN-3:C and the CELF-4 the correlation coefficients were squared and the coefficient of determination was obtained. The CELF-4 was more likely to predict the behavioral results for the largest frequency change ($r^2 = .46$ for the largest frequency change, $r^2 = .26$ for the medium frequency change, and $r^2 = .03$ for the smallest frequency change) than for the other frequency changes; and the SCAN-3:C was more largely correlated to the results for the smallest frequency changes than for the other frequency change ($r^2 = .1$ for the largest frequency change and $r^2 = .21$ for the medium and the smallest frequency changes).

DISCUSSION

Auditory Processing Disorder and Specific Language Impairment

The notion that *pure forms* of APD exist is confirmed by this study, since four participants with *APD only* were identified. Although this group is small, it indicates that some children can have a perceptual deficit as evidenced by below average scores on standardized tests of auditory processing in the absence of other higher order deficits such as SLI or ADD/ADHD. Thus, the idea that a perceptual deficit like APD always causes more general problems in language as proposed by Tallal and colleagues (e.g., Tallal et al., 1993) is not supported. The current study also identified children with *SLI only*. Although this group is small too, it indicates that SLI can be present without underlying auditory perceptual deficits. To be more complete and to further confirm that APD or SLI can be found in isolation, future research should also include reading and writing scores to eliminate the possibility that these children with perceptual auditory deficits or language deficits also have dyslexia, but the current findings support the conclusions reached by Rosen that auditory disorders may be neither sufficient nor necessary in explaining childhood language disorders (Rosen, 2005).

Although APD or SLI are not necessarily co-morbid, the majority of atypically developing children who participated in this study had both APD and SLI. Indeed, the third group of atypically developing children that emerged from this study was the group of children with APD and SLI. This group was larger than the group of children with *APD only* or the group of children with *SLI only* since nine out of seventeen (or 53%) participants with APD or SLI had both. This supports the findings that poor auditory processing ability is often present in children with SLI (e.g., Weber-Fox, Leonard, Wray, & Tomblin, 2010). Weber-Fox and colleagues studied tonal and verbal stimuli electrophysiologically and behaviorally in children with SLI. They confirmed that, although not always present, auditory processing of nonverbal stimuli is

often atypical in children with SLI, especially at rapid presentation rate. However, the correlation between behavioral and electrophysiological results was not significant in the impaired group and poor auditory processing abilities accounted only for a small proportion of the variance in language processing in children with SLI. This also supports the notion that, although APD and SLI are often associated, APD does not cause or predict SLI.

The sample population in the current study was described using commonly used standardized clinical tests: the SCAN-3:C and the CELF-4. As measured by these tests, three distinct groups of atypically developing children were found: a group with *APD only*, a group with *SLI only* and a group with both APD and SLI. However, although children from these different groups presented with distinct clinical profiles, the two standardized tests: the SCAN-3:C and the CELF-4 are not very different. Indeed, correlation coefficients (determined for the 30 participants) indicated the presence of a significant relationship between SCAN:3-C scores and CELF-4 scores ($r = .388$, $p = .03$). This finding underlines the problems of identifying APD using a standardized test like the SCAN:3-C, which includes linguistically loaded subtests (four out of the five subtests of the SCAN:3-C use words) and makes it difficult to differentiate APD from a language deficit. In the future, a better way of describing the sample population with APD might involve using other standardized auditory verbal and auditory nonverbal tests/subtests (e.g., the gap in noise test [GIN]) instead of the SCAN-3:C. But, in the present study the SCAN-3:C was used because it represents common, current clinical practice.

Finally the question of cognitive deficits in pediatric APD should also be addressed in future studies, since a significant proportion of children with APD seem to have significantly lower scores on cognitive measures (e.g., Rosen, Cohen, & Vanniasegaram, 2010). Without implying causality, these findings support the idea that APD is associated with cognitive deficits.

The present study does not support this since all the participants in the current study had average or above average intelligence quotients, but the contradictory results might be explained by the way cognitive abilities were assessed. Rosen and colleagues used a more comprehensive battery to test cognitive abilities, a battery that combined verbal and nonverbal intelligence subtests while the present study only used the TONI-3, a test of nonverbal intelligence designed to avoid language based type of cognitive processing. Further investigation of verbal and nonverbal intelligence abilities in children with APD might be of interest to confirm the possible relationship between APD and higher order processing deficits.

MMN and Behavioral Performance

One purpose of this study was to examine possible differences in children with APD or SLI as measured electrophysiologically or behaviorally. The hypothesis was that pediatric APD was an auditory specific disorder that would be characterized by poor behavioral performances and reduced MMN amplitude on a frequency discrimination task that involved nonverbal stimuli. Although some differences in the amplitude of the MMN were observed between the groups, the most unexpected finding was that the children with *APD only* showed a robust MMN in response to all frequency changes, including the smallest change (2% of the base frequency). In addition, electrophysiological results did not always corroborate behavioral findings, since children with *SLI only* had below chance level hit rates on the smallest frequency change but robust MMN responses. The MMN was expected to be a good predictor of behavioral frequency discrimination abilities (e.g., Pakarinen, Takegata, Rinne, Huotilainen, & Naatanen, 2007). Pakarinen and colleagues investigated how the MMN could be affected by changes in frequency, intensity, duration and phase of nonverbal stimuli. In healthy adults, they found that the

amplitude of the MMN increased and the latency decreased with increased magnitude of change in the sound.

In the current study the MMN was a good predictor of FD hit rates in TD children; this study confirmed the prediction that TD children would be able to discriminate all the frequency changes presented behaviorally and electrophysiologically. In addition, in TD children the larger frequency change elicited greater MMN amplitude than the smaller frequency changes, confirming the observation made by Pakarinen and colleagues that as the magnitude of the stimulus difference decreases the amplitude of the MMN decreases. However, for the atypically developing children, the MMN was not a good predictor of behavioral findings. In fact, for these children the detection of small frequency changes at the level of brain and the formation of a memory trace was not always associated with good behavioral results. Indeed, in children with *SLI only* or *APD only* the MMN was present for all frequency changes even though some of their behavioral results were below chance. This means that the main hypothesis of this study, that poor auditory perceptual abilities could be measured by FD at the level of the MMN, before later processing take place, is not supported by some of the results. The neurophysiological bases of FD might be more complicated than hypothesized.

Since the MMN reflects the detection of a change in a sound before further processing takes place, it is possible that children with *SLI only* show good MMN responses and poor behavioral performances because their brain detects the difference and indexes the creation of a memory trace, but that other neural differences not evidenced by the MMN take place (e.g., Bishop, 2007). Behaviorally, determining if two sounds are the same or different involves detecting the psychoacoustic difference, categorically distinguishing them and making a response. So, psychoacoustic behavioral results reflect pre-conscious auditory abilities as

measured by the MMN as well as, attention, working memory, and decision processes that were not studied explicitly in this experiment.

This finding that behavioral FD results cannot be predicted by the MMN could mean that behavioral FD requires much more than just the detection of an acoustic change and that the MMN alone is not enough to localize where the neural differences occur in children with good MMN but poor behavioral results (see Bishop [2007] for a review on the use of the MMN in the study of APD). Other behavioral tasks might isolate attention, working memory, and decision processes from detection. In addition, fMRI studies might reveal more information about patterns of activation that would elucidate these differences. Further statistical analysis using multi-level modeling might provide some information regarding the association between poor behavioral performances and MMN amplitude.

One explanation for the current findings regarding pediatric APD is that children with *APD only* are less impaired than children with both APD and SLI, which might be why their MMN amplitude is good for all frequency changes. For children who have both APD and SLI, the MMN might be affected because of an inability of the brain to detect the change in frequency; the behavioral scores might be very poor (poorer than for any other groups) because this psychoacoustic perceptual difference evidenced at the level of the MMN is compounded by difficulty with verbal working memory, attention, and decision making rendering the task of judging if two sounds are the same or different very difficult for these children.

Frequency discrimination

Behaviorally, depending on the tasks, it seems that detecting a change or a difference in frequency between two sounds can be more or less difficult (Yost, 2007). The three frequency changes were expected to elicit a 50% or greater score of correct response for the two behavioral

experiments, but the results on the oddball task were better across all groups than the results on the frequency discrimination task. Because the behavioral Δf threshold is 1% of the base frequency at 1000Hz in children with good FD ability (e.g., Moore et al., 2008), 0.7% of the base frequency at 500 Hz, and 0.5% of the base frequency at 3000Hz (Rota-Donahue, 2010), it was presumed that TD children would easily discriminate frequency changes greater than 1% of the base frequency. The typically developing children performed above chance for all the frequency changes on the two behavioral tasks. However, overall results also indicate that behavioral frequency discrimination might involve more complex cognitive processes than a similar detection of frequency changes task using an oddball type of presentation since all participants performed better on the behavioral odd ball task than on the behavioral frequency discrimination task. Indeed a frequency discrimination task involves a direct categorical judgment whereas an oddball task involves detecting a rare change event.

One small difference between children with APD or SLI was found with behavioral results. Although SCAN-3:C scores and CELF-4 scores were related, different relationships were found between these standardized test scores and behavioral hit rates. In fact, the proportion of variance explained by the predictors was significant. The CELF-4 was more strongly correlated to the behavioral results for the largest frequency change and the SCAN-3:C was more likely to predict results for the smallest frequency change. This indicates that, as language skills decrease it is difficult to do well on an easy FD task and hit rate on the largest frequency change go down or children with poor language also have some attentional issues. In contrast, as auditory processing skills measured by the SCAN:3-C decrease, it is more difficult to do well on a challenging FD task and hit rates on the smallest frequency change decrease. This might mean that the underlying brain processes of FD could be different depending on the size of the

frequency change: large frequency changes more affected by non-auditory abilities and small frequency changes by auditory abilities.

Another factor affecting behavioral results is attention (Moore et al., 2008). In terms of hit rates, the poor performers were on average all able to discriminate the 5% frequency change, with hit rates for the 1050Hz frequency change above 50% for all children, including children with APD or SLI. This performance is better than the performance reported by Moore et al. (2008) where poor performers had hit rates $\geq 10\%$ of the base frequency. Attention might have played a more important role than in the current study where all participants were screened for ADD/ADHD and where the length any of the behavioral tasks did not exceed 15 minutes instead of almost one hour for the Moore et al. study.

Absence of evidence of maturational delays

There was no between group difference for P1 and Ta. This suggests that all children in the current study were at the same maturational stage, contrary to previous findings suggesting maturational delays of the P1 in children with SLI (Bishop & McArthur, 2005). In addition, the amplitude of the Ta previously reported to be attenuated in children with SLI in response to speech (Shafer et al., 2011) was not significantly attenuated in the impaired groups in response to tones in this study.

Theoretical implications

The notion that auditory processing can be explained using the continuum model (Richard, 2001) where all information is processed sequentially: first auditorily then linguistically is not supported by the current findings. This model states that auditory processing follows a linear series of neural activations from the cochlea to the auditory cortex and then higher order cortical regions, where the auditory pathways first processes sounds acoustically,

then in terms of phonology if the sound is recognized as being a speech sound and finally lexically, morphologically, or syntactically at higher cortical levels. But to support that model, children with *APD only* and children *with SLI only* would have had to differ on a basic auditory task of FD, a nonverbal measure thought to reflect auditory processing ability before sounds are processed linguistically and at a conscious level. However, children with *APD only* did not show evidence of an auditory specific deficit as measured behaviorally and by the MMN. Instead, children with *APD only* and children with *SLI only* performed similarly and, only the *BOTH* group differed.

Children with *APD only* and children with *SLI only* were more similar than different in terms of behavioral and electrophysiological results. This too contradicts the assumption that children with APD would have an auditory specific problem as measured by the MMN, but that children with SLI would not, because the processing problem for children with SLI would be higher up and not evidenced at the level of the MMN. The prediction that children with *APD only* and children with *SLI only* would exhibit differences behaviorally and electrophysiologically is not supported by the results of this study, which might indicate that APD is not an auditory specific deficit evidenced at the level of basic auditory detection of small frequency changes that would be reflected by MMN findings.

The *BOTH* group was the only group that exhibited reduced/absent MMN amplitude to small frequency changes. As expected, this group differed from the other groups: the sensitivity indexes for the behavioral tasks were below chance level for some of the frequency changes and the MMN responses were reduced or absent. The *BOTH* group displayed a combination of significantly poorer behavioral FD than all the other groups, and reduced/absent MMN amplitude to all the frequency changes. This indicates that the MMN was affected only in the

children who were more severely impaired. In fact the children in the *BOTH* group had the worst behavioral FD scores (their behavioral performances were statistically poorer than that of the other children) and this group was the only group to have reduced/absent MMN amplitudes. Therefore the linear model of processing (Cacace & McFarland, 2005, Richard, 2001) is too simplistic to explain auditory processing and top down influences appear to have an effect on a task as simple as frequency discrimination of pure tones. A more complex model involving an interpretation between auditory perception and language abilities is more likely to explain these findings (Bishop, 2007).

Further research is needed to confirm these observations, characterize auditory processing, and confirm the prevalence of SLI in children with APD. Since the processing of small frequency changes is complex, future studies could also include other types of neurophysiological measures than electrophysiology, such as the fMRI. In addition, looking at reading skills and working memory in children with APD might further determine if APD is a perceptual deficit independent from higher order deficits or not. At this time, this study shows that children with *APD only* (and no SLI or ADD/ADHD) can be found. However, the electrophysiological and behavioral profiles of these children with *APD only* are not different from those of children with *SLI only*. So, further investigations are needed to explore the question of *pure forms* of APD that might be supported by identifiable biological markers of the disorder.

Appendix

Table A Groups and standard scores for the 30 participants on the CELF-4 subtests (CFD, WC-R, RS, FS, WC-E), the CELF-4 Core Language, Receptive Language, Expressive Language, the SCAN-3 subtests (AFG, FW, CW, CS, Gap), SCAN composite and the TONI-3.

GROUP	CFD	WC-R	RS	FS	WC-E	CLS	RLS	ELS	AFG	FW	CW	CS	Gap	Composi	TONI-3
APD	12	12	12	12	13	12	115	109	112	5	9	9	10	5	80
APD	9	9	13	13	9	10	104	93	103	7	11	11	14	5	90
APD	8	9	8	8	12	10	100	90	99	10	10	7	12	5	90
APD	12	8	12	12	9	10	102	100	101	6	10	8	11	6	85
BOTH	4	6	4	4	4	4	64	73	61	8	11	7	12	6	96
BOTH	5	6	6	6	6	3	73	76	69	5	11	10	11	7	94
BOTH	3	9	7	7	13	13	97	79	105	6	10	13	13	5	96
BOTH	1	5	2	2	2	5	54	61	57	6	6	3	4	8	65
BOTH	4	5	7	7	11	6	85	58	89	8	9	4	9	8	83
BOTH	10	7	10	10	4	9	90	90	87	6	11	8	9	6	89
BOTH	1	9	1	1	2	4	54	64	59	7	8	7	7	12	81
BOTH	12	10	2	2	8	11	93	105	83	6	8	6	9	9	81
BOTH	3	8	2	2	1	9	60	76	63	12	7	5	7	12	83
SLI	8	6	5	5	5	9	76	64	77	10	10	12	12	12	107
SLI	6	8	9	9	9	8	90	83	93	8	15	11	13	12	113
SLI	10	6	10	10	2	9	87	88	82	8	11	12	14	10	109
SLI	13	4	12	12	3	5	90	90	80	7	12	10	10	10	98
TD	12	11	10	10	11	10	102	109	101	10	11	10	12	12	105
TD	12	16	16	16	15	16	134	125	134	10	9	8	12	10	98
TD	12	13	14	14	10	13	114	102	114	7	10	12	11	10	98
TD	7	12	13	13	13	17	118	96	124	12	12	16	12	10	123
TD	12	12	12	12	12	12	112	105	110	8	10	8	8	10	89
TD	13	13	13	13	14	14	127	119	122	8	9	12	11	10	100
TD	13	16	11	11	16	18	129	122	130	10	11	13	12	12	111
TD	14	7	10	10	13	11	96	102	108	10	10	14	11	10	109
TD	13	13	15	15	15	16	129	119	132	7	11	11	12	9	101
TD	10	10	12	12	9	11	109	102	103	10	11	13	12	10	111
TD	14	16	12	12	14	17	127	131	126	10	9	9	8	8	92
TD	10	9	11	11	6	10	94	93	95	8	12	10	9	12	98
TD	8	9	10	10	10	9	95	93	98	12	12	11	13	10	115
Means for the group of Typically Developing children (TD) and for the group of Atypically Developing children (AT)															
MeanTD	12	12	12	12	12	13	114	109	115	9	11	11	11	10	104
MeanAT	7	7	7	7	7	8	84	82	84	7	10	9	10	8	91

Table B Summary of tests scores for the APD only group, the SLI only group, and the group of children with both APD and SLI on the CELF-4 CORE Language (CLS), Receptive Language (RLS), Expressive Language (ELS), the SCAN-3 composite and the TONI-3.

	APD (n=4)				SLI (n=4)				BOTH APD and SLI (n=9)			
	Mean	SD	SE	Range	Mean	SD	SE	Range	Mean	SD	SE	Range
CLS	105		7	3 100-115	86		7	3 54-97	74		17	6 76-90
RLS	98		8	4 90-109	81		12	6 64-90	76		15	5 58-105
ELS	104		6	3 99-112	83		7	3 77-93	75		17	6 57-105
SCAN-3	95		7	3 87-101	107		6	3 98-113	86		11	4 65-103
TONI-3 Quotient	100		12	6 82-110	103		6	3 98-111	98		8	3 87-115

Appendix C:**ASSENT FORM (CHILDREN 12 year-old) AND****ORAL SCRIPT (CHILDREN younger than 12 year-old)**

I am inviting you to be in a research study that will be done in two sessions. I will describe the study to you so that you can decide whether or not you want to do it. Feel free to ask any questions at any time.

Title of the study: Brain Bases of Spectral Processing in Pediatric Auditory Processing Disorder

Goal of the study: In this study you will do a computer game that measures your response to sounds that are the same and to sounds that are different. I will also measure your brain waves to the same sounds.

What you will do: The first time you come, I will ask you to raise your hand when you hear a sound. I will also ask you to repeat words/sentences and to answer questions. Then you will do a short computer game where you will listen to sounds and let me know if they are the same or different. The second time you come, you will wear a special hat with wires on it. The hat is used to measure your brain waves so that we can see them. The hat does not hurt. Your head will be rubbed and gel will be squirted into the hat so that it makes good contact. It will feel a little tight. Once the hat is in place, you will listen to some sounds while you watch a video with no sound. I will then ask you a few questions about the video. You can have a break whenever you need one, just ask.

How long it will be: You will come twice for about 2 hours each time, (you might have to come a third time if you get tired).

Does it hurt? No, nothing in this study is painful. Your skin might become a little red from placement of the hat, if this happens, it should go away in a few days.

What is this study good for? You will get free hearing, listening and language screenings. When finished, you can pick out a prize to take home. The results of this test will be good for science and may also help children with auditory processing disorder.

Do I have to do the study if I don't want to? No, if you agree to do this study, I want to make sure that you understand that it is absolutely up to you. If you decide that you no longer want to do it you can stop at anytime. I also want you to know that I will not use your name in any way connected to the study.

For questions about the study: Contact Christine Rota-Donahue, M.Phil., CCC-A/SLP, Principal Investigator and Doctoral Candidate, Program in Speech-Language-Hearing Sciences, The Graduate Center, The City University of New York, 365 Fifth Avenue, New York, NY 10016, 212-817-8812, crota-donahue@gc.cuny.edu. You can also contact Richard Schwartz, Director of the Developmental Language Laboratory, Program in Speech-Language-Hearing Sciences, The Graduate Center, The City University of New York, 365 Fifth Avenue, New York, NY 10016, 212-817-8804, rschwartz@gc.cuny.edu.

For questions about your rights: If you have any questions about your rights as a research participant, you may contact Kay Powell, IRB Administrator, The Graduate Center, The City University of New York, 365 Fifth Avenue, New York, NY 10016, 212-817-7525, kpowell@gc.cuny.edu.

Questions: Please answer Yes or No for these two questions:

Do you have any questions about the study? _____ Yes _____ No

Do you agree to participate in the study? _____ Yes _____ No

Name of the Research Participant: _____

Name of Parent/Guardian: _____

Signature of Research Participant

Name of Researcher

Date

Signature

PARENTAL/GUARDIAN PERMISSION FORM**FOR PARTICIPANTS younger than 18 year-old**

The purpose of this permission form is to provide you with information you need in order to decide whether you want your child to participate in this research project. Please read the information below carefully. You are encouraged to ask questions before deciding whether to give permission for your child to participate in the study, and to ask questions at any time during the course of the study.

Project Title: Brain Bases of Spectral Processing in Pediatric Auditory Processing Disorder

Principal Investigator: Christine Rota-Donahue, M.Phil., CCC-A/SLP, Doctoral Candidate, Speech-Language-Hearing Sciences Program, The Graduate Center, The City University of New York.

Purpose: The purpose of this study is to measure brain processing of small frequency changes and compare results with behavioral measures of frequency discrimination of these changes. The findings might help children with Auditory Processing Disorder.

Procedure: During the first session I will screen your child's hearing, auditory processing, language, cognitive and attention abilities by asking him/her to repeat words/sentences and to answer questions and by asking you to fill out a questionnaire (see consent form). Then your child will be asked to listen to tones and determine if there are the same or different. During the second sessions your child's hearing will be screened again. Then, a cap with electrodes will be placed on his/her scalp using the standard clinical Electroencephalography (EEG) procedure. Before placing the cap, your child's scalp will be rubbed with alcohol. Gel will help good contact of the electrodes with the scalp. The gel can easily be removed after the test. During the test, brain responses to sounds will be recorded while your child watches a silent video. Your child will be asked to answer a few questions about the video afterward.

Time Involvement: Testing takes two sessions each lasting about 2 hours, (another session might be needed if your child gets tired). You will be compensated \$15/hour for your child's participation.

Risks: There are no known risks to using behavioral or EEG techniques to test frequency discrimination abilities. Minor skin irritation that clears up within a few days is occasionally present at electrodes sites.

Benefits: Your child will get free screenings. Otherwise, there are no direct benefits to participants. Your decision whether or not to have your child participate in this study will not affect your treatment by staff and this institution. If you are a student, your decision to participate or not will not affect your grade in any course, and if you are an employee, your employment and treatment by staff will not be affected by your decision. **Confidentiality:** I will not use your name or your child's name in any way connected to this study. All data will be coded and the key to the code will be locked in a cabinet. Only the principal investigator will have access to the code. In addition, the records may be inspected by the CUNY Institutional Research Board.

Voluntary Participation: Your child's participation in this study is voluntary. You and your child have the right to decline to participate, to withdraw your consent, or to discontinue participation at any time without penalty. You and your child have the right to refuse to answer particular questions. Your signature below indicates that you have voluntarily decided to allow your child to participate in the study.

Please note that testing can be discontinued or rescheduled by the researcher if it becomes clear that your child does not wish to participate, becomes excessively fatigued, or stops cooperating.

Compensation: Participants receive \$15 per hour for their participation.

Number of Participants: The estimated number of participants for this study is 40.

For questions about the study: Contact Christine Rota-Donahue, M.Phil., CCC-A/SLP, Principal Investigator and Doctoral Candidate, Program in Speech-Language-Hearing Sciences, The Graduate Center, The City University of New York, 365 Fifth Avenue, New York, NY 10016, 212-817-8812, crota-donahue@gc.cuny.edu. You can also contact Richard Schwartz, Director of the Developmental Language Laboratory, Program in Speech-Language-Hearing Sciences, The Graduate Center, The City University of New York, 365 Fifth Avenue, New York, NY 10016, 212-817-8804, rschwartz@gc.cuny.edu.

For questions about your rights: If you have any questions about your rights as a research participant, you may contact Kay Powell, IRB Administrator, The Graduate Center, The City University of New York, 365 Fifth Avenue, New York, NY 10016, 212-817-7525, kpowell@gc.cuny.edu.

The extra copy of this permission form is for you to keep. A summary of the study results will be provided to you upon request.

If you have read this form and have decided to allow your child to participate in this research, please sign below.

Name of the Research Participant: _____

Name of Parent/Guardian
Date

Signature

Name of Researcher
Date

Signature

Graph D: Distribution of standard scores obtained on the Core Language, Receptive Language, Expressive Language of the CELF-4, the auditory processing composite of the SCAN-3 and the test of non-verbal intelligence TONI-3.

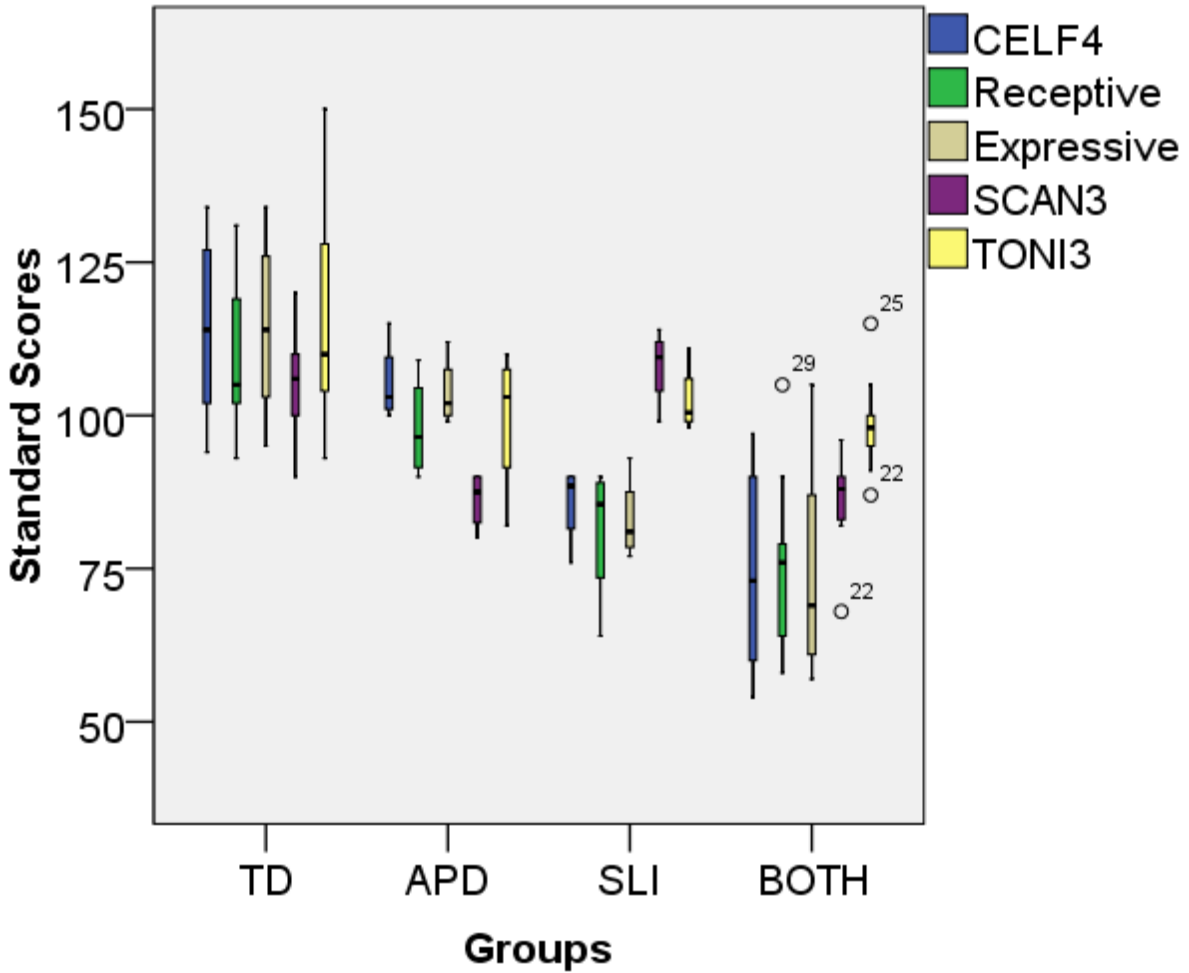
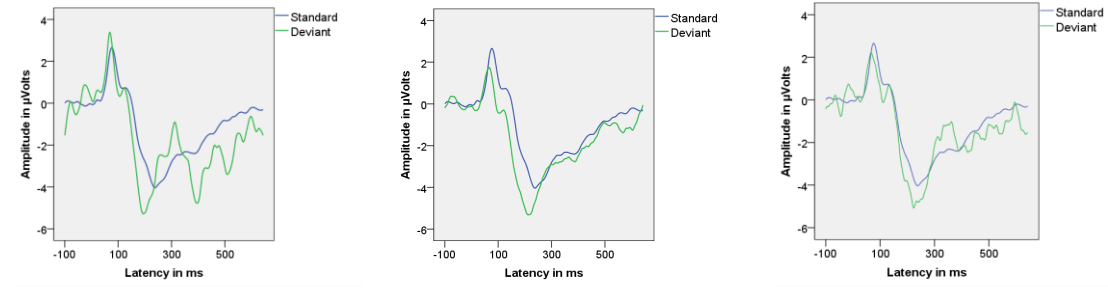


Table E: Significance level, mean difference and standard error of the difference between the typically developing children and the children with APD or SLI for the core language, receptive language, expressive language, auditory processing composite and nonverbal IQ scores.

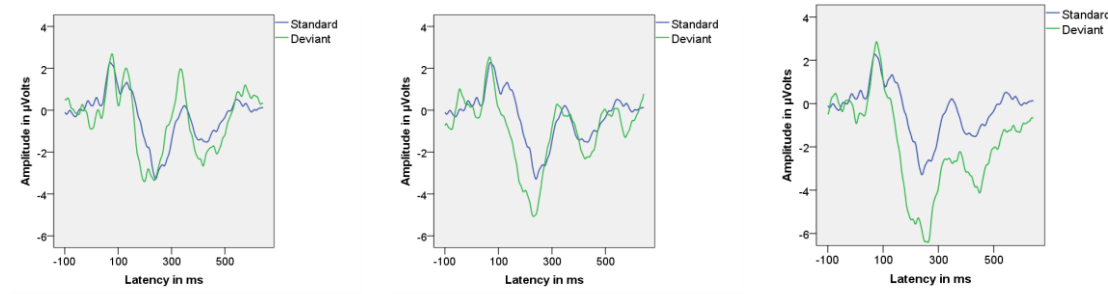
	Significance 2 tailed t test	Mean difference	SE difference
CELF-4 Core	0.000	30	6
CELF-4 Receptive	0.000	27	5
CELF- 4 Expressive	0.000	32	6
SCAN-3 Composite s	0.014	11	4
TONI-3 Quotient	0.001	17	5

Figure F: Groups' standard (in blue) and deviant (in green) waveforms at Fz for – from left to right - the 1150Hz, 1050Hz and 1020Hz frequency changes respectively.

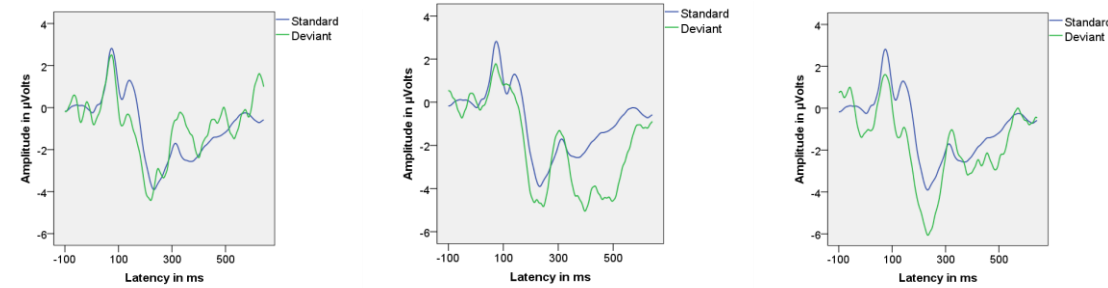
TD group



APD group



SLI group



BOTH group

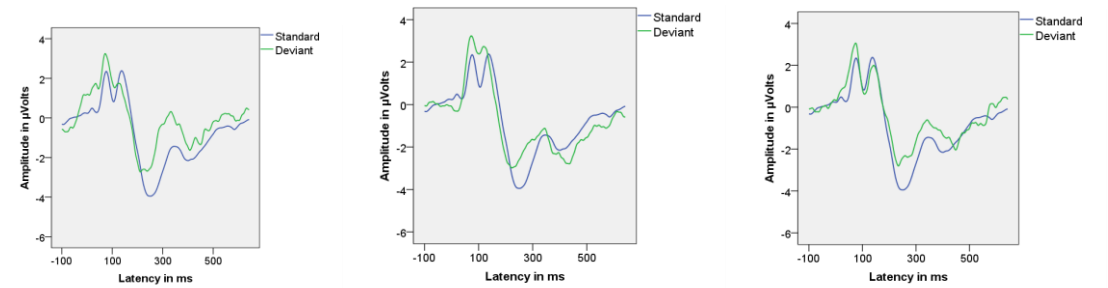
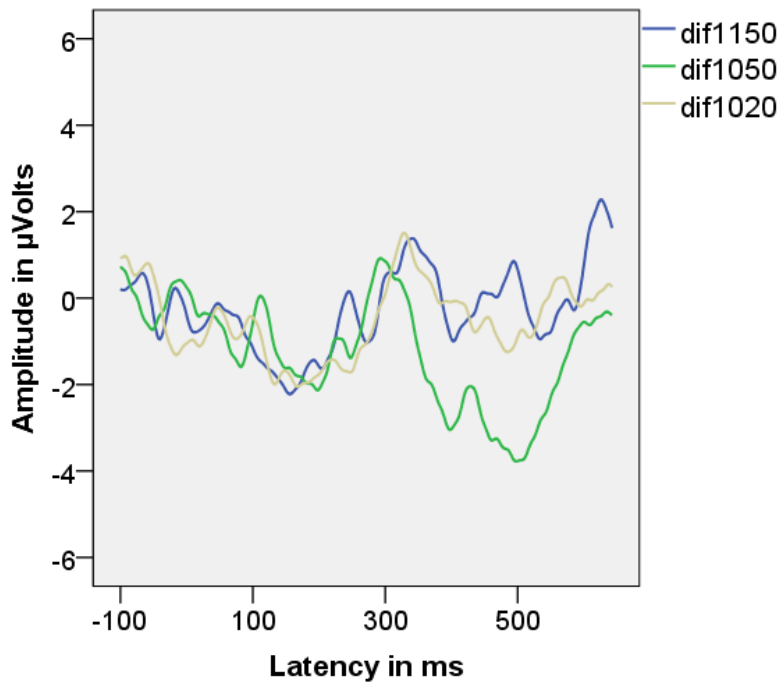
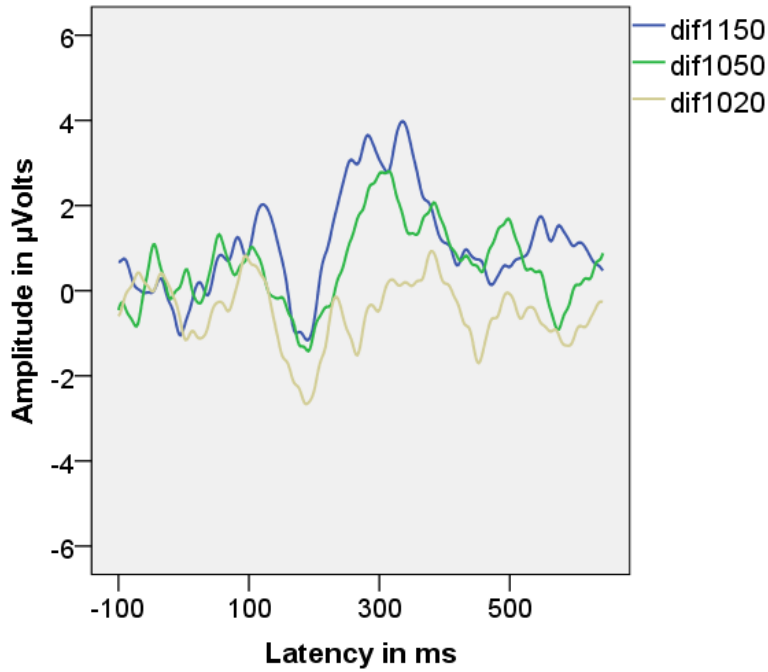
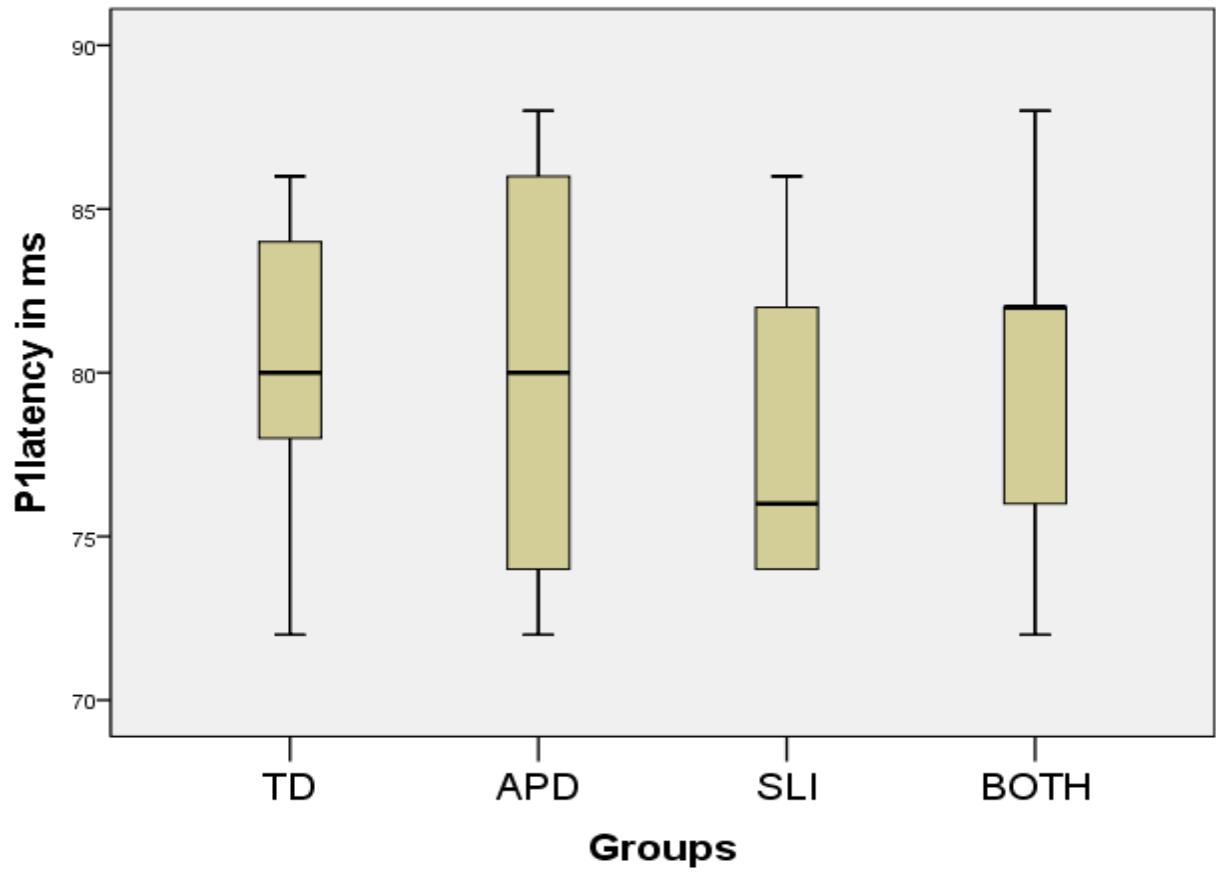


Figure G: MMN difference waveforms for the APD group and for the SLI group for the three frequency changes.



Graph H1: P1 latency at FCz for the four groups of participants



Graph H2: P1 amplitude at FCz for the four groups of participants

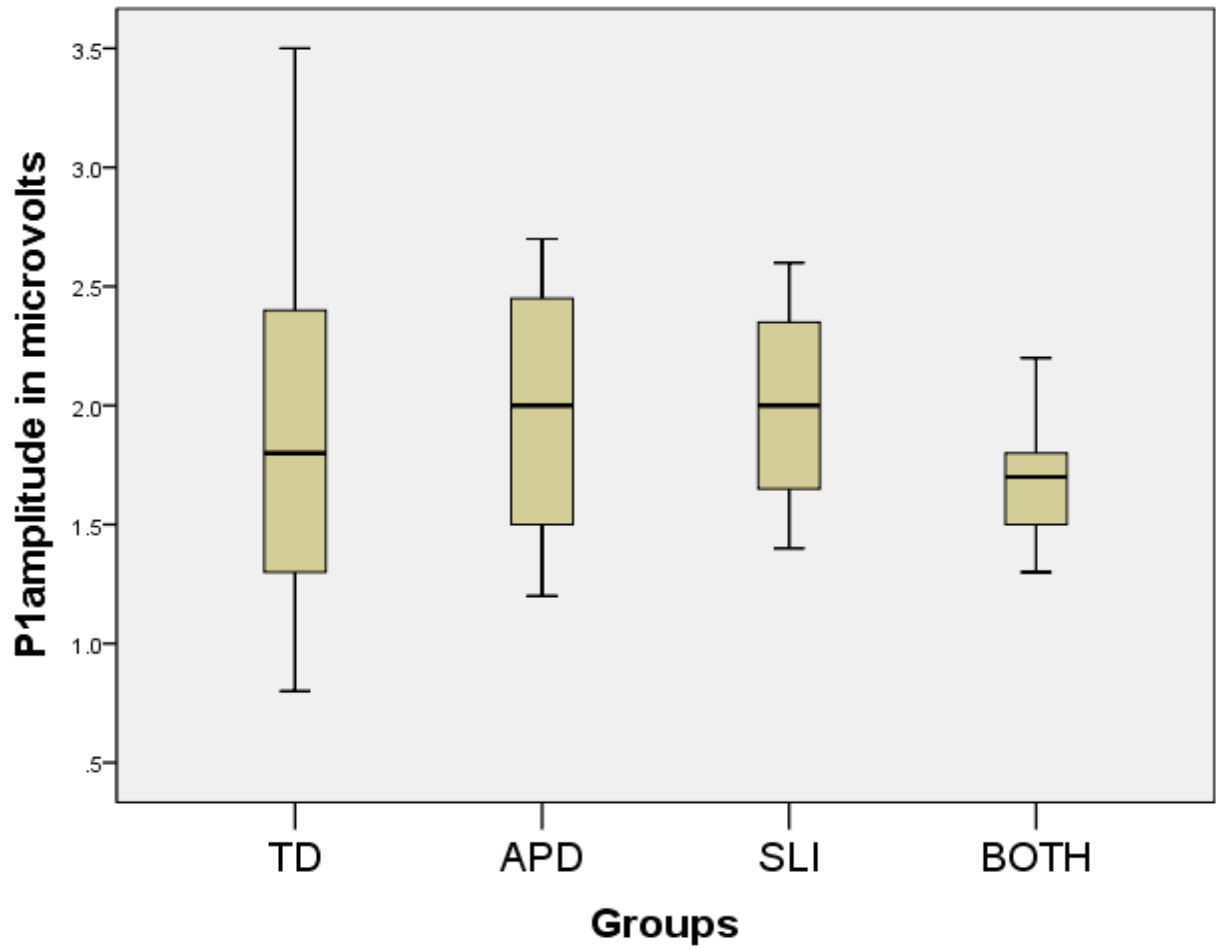


Table I: Average amplitude in μ Volts of Ta at T7 and T8 sites for the four groups of participants

	TD	APD	SLI	BOTH
T7	0.4	0.2	0.2	0.4
T8	1.2	0.5	0.3	0.6

Table J: *M* hit rates and *SD* for the behavioral tasks for each group

		Report					
Group2		Diff1020	Diff1050	Diff1150	OB1020	OB1050	OB1150
1	Mean	55.38	87.31	97.31	60.7692	85.0000	91.5385
	N	13	13	13	13	13	13
	Std. Deviation	24.278	9.707	5.633	28.71165	14.28869	5.54700
2	Mean	36.25	62.50	90.00	46.2500	76.2500	95.0000
	N	4	4	4	4	4	4
	Std. Deviation	23.936	34.278	14.142	26.57536	38.16084	4.08248
3	Mean	42.50	71.25	88.75	48.7500	78.7500	80.0000
	N	4	4	4	4	4	4
	Std. Deviation	29.011	16.520	7.500	11.81454	11.08678	12.24745
4	Mean	43.33	65.00	79.44	39.4444	55.0000	61.6667
	N	9	9	9	9	9	9
	Std. Deviation	23.318	21.794	20.683	30.25356	36.57185	40.23369
Total	Mean	47.50	75.17	89.83	50.8333	74.0000	81.5000
	N	30	30	30	30	30	30
	Std. Deviation	24.380	21.029	14.709	27.73282	28.05168	25.86937

Table K1. Frequency discrimination task, $M d'$ for the three frequency changes

	TD	APD	SLI	BOTH
1020	1.94	1.24	0.89	0.9
1050	3.1	2.05	1.96	1.6
1150	3.85	3.28	2.63	2.17

Table K2. Oddball task, $M d'$ for the three frequency changes

	TD	APD	SLI	BOTH
1020	2.54	2.14	2.3	1.65
1050	3.45	3.47	3.18	2.09
1150	3.72	3.33	4.05	2.93

Table L - Correlations between MMN amplitude for the three frequency changes and behavioral results

	MMNA1150	MMNA1050	MMNA1020	Diff1150	Diff1050	Diff1020	OB1150	OB1050	OB1020	CELFA	SCAN3
MMNA 1150	1	0.173	.478	-0.233	-0.174	-0.165	-0.23	-0.257	-0.146	-0.369	-0.341
		0.361	0.008	0.215	0.359	0.385	0.222	0.171	0.441	0.045	0.065
		30	30	30	30	30	30	30	30	30	30
MMNA 1050	0.173	1	-0.129	0.201	0.198	0.296	0.175	-0.129	-0.087	0.287	0.143
	0.361	0.008	0.495	0.287	0.295	0.113	0.356	0.498	0.649	0.125	0.451
	30	30	30	30	30	30	30	30	30	30	30
MMNA 1020	.478	-0.129	1	-0.151	-0.069	0.108	-0.147	-0.07	0.165	-0.328	-0.093
	0.008	0.495	0.287	0.424	0.719	0.57	0.437	0.714	0.384	0.077	0.625
	30	30	30	30	30	30	30	30	30	30	30
Diff1150	-0.233	0.201	-0.151	1	.688	0.285	.624	.472	0.332	.676	0.304
	0.215	0.287	0.424	0.688	0	0.127	0	0.008	0.073	0	0.103
	30	30	30	30	30	30	30	30	30	30	30
Diff1050	-0.174	0.198	-0.069	.688	1	.573	.584	.485	.539	.508	.467
	0.359	0.295	0.719	0	0.001	0.001	0.001	0.007	0.002	0.004	0.009
	30	30	30	30	30	30	30	30	30	30	30
Diff1020	-0.165	0.296	0.57	0.285	.573	1	0.344	0.231	.477	0.179	.419
	0.385	0.113	0.437	0.624	0.001	0.063	0.063	0.22	0.008	0.345	0.021
	30	30	30	30	30	30	30	30	30	30	30
OB1150	-0.23	0.175	-0.147	.804	.584	0.344	1	.804	.633	.551	.379
	0.257	0.356	0.437	0	0.001	0.063	0	0	0	0.002	0.039
	30	30	30	30	30	30	30	30	30	30	30
OB1050	-0.146	-0.129	-0.07	.472	.485	0.231	.804	1	.791	.518	.422
	0.441	0.498	0.714	0.008	0.007	0.22	0	0	0	0.003	0.02
	30	30	30	30	30	30	30	30	30	30	30
OB1020	-0.146	-0.087	0.165	0.332	.539	.477	.633	.791	1	0.34	.440
	0.441	0.649	0.384	0.073	0.002	0.008	0	0	0	0.066	0.015
	30	30	30	30	30	30	30	30	30	30	30
CELFA	-0.369	0.287	-0.328	.676	.508	0.179	.551	.518	0.34	1	.388
	0.045	0.125	0.077	0	0.004	0.345	0.002	0.003	0.066	0.066	0.034
	30	30	30	30	30	30	30	30	30	30	30
SCAN3	-0.341	0.143	-0.093	0.304	.467	.419	.379	.422	.440	.388	1
	0.065	0.451	0.625	0.103	0.009	0.021	0.039	0.02	0.015	0.034	0.034
	30	30	30	30	30	30	30	30	30	30	30

**, Correlation is significant at the 0.01 level (2-tailed).

*, Correlation is significant at the 0.05 level (2-tailed).

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