



Research paper

Auditory processing disorder evaluations and cognitive profiles of children with specific learning disorder

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ABSTRACT

Objective: This study investigated the auditory sensory-perceptual level of specific learning disorder (SLD) and explored relationships among neuropsychological assessments for SLD, auditory processing, and short and long latencies of auditory event-related potentials (ERPs).

Methods: Fifteen children (7–14 years old) comprised the control group; 34 children comprised the SLD group. Audiologic assessments included tone audiometry, acoustic immittance measurements, acoustic reflex, central auditory processing, brainstem evoked response audiometry, and long latency potentials (P3 and N2). Children's intelligence levels were assessed with 2 intelligence batteries, 1 verbal and 1 non-verbal, as well as with visuomotor skills.

Results: Multiple regression showed a significant interaction effect of APE tests and P3/N2 over Wechsler Scale performance in freedom of distractibility indexes and multiple subtests. Errors in the Bender Visual Motor Gestalt Test were predicted by lower parental education, lower performance in APE tests: dichotic digits and pediatric/synthetic sentence identification-ipsilateral, and longer P3/N2 latencies, particularly regarding integration and rotation distortions.

Conclusions: Children with altered auditory processing exhibit a specific cognitive profile, including lower verbal and spatial reasoning performance, that is sensitive to parental education level.

Significance: Children with SLD should undergo a complete multimodal examination to identify their specific difficulties and needs.

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1. Introduction

Specific learning disorder (SLD) is related to difficulties in learning and in the use of academic skills (American Psychiatry

Association [APA], 2013). At least one symptom among comprehending difficulties in reading, writing, and academic skills must be present for a definite diagnosis. SLD affects 1–2.5% of the occidental population and encompasses different conditions that lead to functional disorders; it requires monitoring and interventions throughout life, including regular medical follow-ups and health-care interventions (Gillberg and Soderstrom, 2003). There are different factors that may interfere with the identification of SLD, such as temporal processing alterations, auditory processing disorders (APD), eye movement alterations during reading, and attention deficit and hyperactivity disorder (ADHD), among other comorbidities, which contributes to the complexity of the assessment and to the necessity of designing effective interventions. For instance, the comorbidity of SLD and ADHD is relatively high, with approximately 31–45% of students with ADHD also having SLD and vice versa (DuPaul et al., 2013; Al-Yagon, 2015). Other studies report comorbidity with Dyslexia (Banai and Ahissar, 2006; Iliadou et al., 2009; Hämäläinen et al., 2012). Approximately

Abbreviations: SLD, specific learning disorder; APD, auditory processing disorders; ADHD, attention deficit and hyperactivity disorder; DD, dichotic digits test-double pairs; SN, speech in noise test; PSI/SSI, synthetic sentence identification test; SSW, staggered spondaic words; LOC, localization in five directions; ERP, event-related potential; BERA, brainstem evoked response audiometry; TA, tone audiometry; APE, auditory processing evaluation; WISC, Wechsler Intelligence Scale for Children; IQ, intelligence quotient; VIQ, verbal intelligence quotient; PIQ, performance intelligence quotient; FSIQ, full scale intelligence quotient; VCI, Verbal Comprehension Index; PRI, Perceptual Reasoning Index; PSI, Processing Speed Index; FDI, Freedom from Distractibility Index; SON-R test, Snijders-Oomen Non-verbal Intelligence Test; BGT, Bender Visual Motor Gestalt Test; LD, learning disability.

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10% of the general population is expected to be in an abnormal range for learning skills, of which 37% will present with comorbid dyslexia and 46% with comorbid APD (Dawes and Bishop, 2010), such that APD is a possibly strong complicating factor in SLD cases. Thus, any children suspected to have APD should undergo through a complete psychometric assessment (Rosen et al., 2010). Testing for APD includes an evaluation of the child's auditory abilities through behavioral observation of their performance on different tasks, such as the identification of the direction of a sound source, the identification of words and/or phrases heard in competitive or distorted acoustic conditions, or the identification of syllable-type sounds and brief pure tones. This type of evaluation enables identification of the child's auditory disabilities and their type of gnostic impairment, that is, the specific association between hearing disability and language learning that a child is confronted with.

Central APD was defined by American Speech Language Hearing Association (ASHA) in 1993 (Katz, 1992) as difficulties with: sound localization, auditory discrimination and pattern recognition, temporal resolution/masking/integration/ordering, and/or auditory performance with degraded and competing signals. Individuals with deficits in central auditory functions frequently demonstrate good abilities to detect pure tones and to hold conversations in acoustically silent environments, measured by pure-tone audiometry and speech audiometry. Therefore, sensitive auditory measures for the identification of APDs are those that use stimuli with some type of distortion in their time, frequency, and intensity, or those that introduce monotone sound competition in the same ear or in the opposite ear in a dichotic task. In addition, in individuals with an APD, immittance measurements are generally normal. Eventually, the acoustic reflexes may be altered or absent, with the rest of the basic audiologic evaluation being normal (Engelmann and Ferreira, 2009; Bellis, 2011). In 2016, the Brazilian Academy of Audiology Pereira et al. (2018) suggested that a battery of auditory evaluations should contain one test for each of the following processes: binaural interaction, dichotic listening, temporal processing, auditory figure-ground, auditory closure, and monaurally low redundancy listening. Altogether these functions can be categorized in four basic dimensions, as suggested by Katz (1992): Decoding, Tolerance Fading memory, Integration, and Organization; or by Bellis (2011): decoding, associative, integration, and organization-output deficits. Alternatively, they can also be classified as temporal processing, decoding, coding, and integration or binaural fusion (Engelmann and Ferreira, 2009; Pereira and Schochat, 1997). The integrity of the four dimensions can be measured by tests typically administered for central hearing; examples, from among a great variety, are as follows: *Temporal patterning* by the Pitch Pattern Sequence Test; *Decoding* by dichotic digits test-double pairs (DD) to evaluate the auditory figure-ground perception ability for verbal sounds, and the speech in noise test (SN) assesses difficulty in understanding speech against background noise; *Coding* by the pediatric/synthetic sentence identification test (PSI/SSI) and staggered spondaic words (SSW) to evaluate auditory gnostic processes; *Binaural integration by Rapid Alternating Speech and the test localization in five directions* (LOC) (see more in Katz, 1992; Ferre, 2006; Bellis, 2011).

APD may be associated with difficulties in listening, speech understanding, language development, and learning, but it is conceptualized as a deficit in the processing of auditory input and can either occur independently or coexist with other perceptual disorders (Hood and Berlin, 2003). The search for specific cognitive or learning style profiles in children with neurodevelopment disorders has provided evidence that these individuals do not consolidate and retain sequence knowledge as effectively as other children with learning disadvantages in specific areas, for instance children with specific language impairments that present as difficulties in grammatical skills but not in vocabulary (Krishnan et al.,

2016). Gnostic deficits of the decoding type are those in which auditory disabilities are associated with impairments of analysis and synthesis of speech sounds. Gnostic deficits of the coding type are those in which auditory disabilities are associated with impairments of sensory integration in language learning. Gnostic deficits of the organizational type are those in which auditory disabilities are related to the inability to represent sound events in time (Bishop, 2014; Sussman et al., 2015). The aetiology of central APDs includes frequent otitis in early childhood, high and continuous fevers, specific developmental disorders of auditory function, minor lesions in the conduction pathways, and sensory deprivation during early childhood (Engelmann and Ferreira, 2009).

Although it has been suggested that APD might contribute to lower academic performance and literacy skills, no direct relationship has so far been found between auditory impairments and measures of cognitive skills (Rosen et al., 2010). This study thus aimed to investigate the auditory sensory-perceptual level of SLD and to explore the relations among neuropsychological assessments for SLD, auditory processing, and short and long latencies of auditory event-related potentials (ERPs). The methods used comprise an auditory processing battery based on the Jerger and Musiek (2000) assessment model, electrophysiologic and electroacoustic testing, and intelligence tests for verbal and executive functions that include visuomotor performance tests. The audiologic evaluation will test ears separately even for central potentials as the peripheral way can influence the neural path impacting in the latency of each potential, or even in the morphology of the most peripheral waves. We expected to find that individuals with APD have poorer scores on verbal function tests, as a predictor of speech recognition, communication, and listening skills, while their general domains of executive functions and cognition are preserved (Miller, 2011).

2. Methods

The participants in this cross-sectional observational study were recruited through clinician referrals in the Neuropediatric Unit of the University of Brasilia Hospital, in the ward especially dedicated to SLDs. Inclusion criteria were complaints of SLD for at least 1 year and at least 6 months of clinical monitoring that indicated an SLD diagnosis based on the DSM-5 (APA, 2013). The patients' medical records were assessed, and participants were excluded when they had a 5-minute Apgar score of less than 7 at birth, a history of hearing loss, metabolic, respiratory, cardiovascular, neurological, or infectious diseases or prematurity, or cardiac and neurological congenital malformations. It was also excluded children with or under investigation for comorbidities with other neurodevelopmental disorders. Fifteen control group participants and 41 participants originally diagnosed with SLD met the inclusion criteria and thus represented the initial sample that was retested and underwent audiologic screening, as described below. Among these, 4 participants failed the brainstem evoked response audiometry (BERA) test, as retrocochlear alterations were found, and 3 showed altered values in ERPs that were highly suggestive of attention disorder. All the excluded participants all were referred to the appropriate outpatient clinic. Hence, the final sample consisted of 15 children in the reference group, including 10 males (66.7%), with a mean age of 10.87 (± 2.17) years, and an age range of 7–14 years; there were 34 children in the SLD group, including 23 males (67.6%), with a mean age of 10.45 (± 2.14) years, and an age range of 7–14 years. Written informed consent was obtained from parents before the inclusion of their child in the study, which was performed in accordance with the Declaration of Helsinki [WHO] and approved by the Research Ethics Committee of the University of Brasilia. The data are not available for public

access because of patient privacy concerns, but are available from the corresponding author on reasonable request.

2.1. Procedure

The participants were firstly submitted to an audiologic evaluation including tone audiometry, acoustic immittance measurements, assessment of the acoustic reflex, a central auditory processing evaluation (APE), BERA measurements, and an exploration of long latency potentials (P3 and N2) that are related to attention and to the cognitive domain of the auditory response (Zeigelboimet al., 2010). All audiologic tests were conducted in the same environment and by the same trained audiologist, as a trained neuropsychologist conducted all cognitive and visuomotor tests in another setting. Both professionals were blind to the testing results of the each other. Secondly, the children's intelligence level was assessed with 2 intelligence batteries, 1 verbal and 1 non-verbal, as well as their visuomotor skills. All tests were performed in the same week, whenever possible on successive days, and required an average of 3 days for completion. The procedure flowchart is presented in Fig. 1.

2.2. Instruments

2.2.1. Audiologic assessment

The audiologic evaluation was conducted by tone audiometry (TA) (Model Beta6000, Betamedical, São Paulo, Brazil) and impedance testing with an impedance audiometer (Model AT325, Interacoustics, Assen, Denmark). Tympanometry, with a probe frequency of -226 Hz, was used to test the tympanic reflex at frequencies of 0.5, 1, 2, and 4 kHz. Audiometry verified air conduction at frequencies of 0.25, 0.5, 1, 2, 4, and 8 kHz, and bone conduction

at frequencies of .5, 1, 2, 3, and 4 kHz. Children were screened to ensure that they had pure-tone hearing thresholds of 20 dB HL or better between 0.5 and 4 kHz and type A tympanograms bilaterally (Miller and Wagstaff, 2011).

2.2.2. Electrophysiology

Brainstem and cortical auditory evoked potentials were recorded to evaluate auditory latency and attention sustantation skills; these were investigated by BERA and by ERPs (Model Navigator Pro, Biologic Systems, Mundelein, IL, USA). BERA yields auditory brainstem responses in a series of 6 to 7 vertex-positive waves of WI, WIII, and WV, as well as interpeaks WI-III, WIII-V, and WI-V; all are evaluated at 80 dBnHL. These waves occur in the first 10 ms after onset of an auditory stimulus (Burkard et al., 2007). Brainstem evoked responses were bilaterally elicited using a rarefaction click frequency of 27.7 stimuli per second, with low-pass filter at 100 Hz and high-pass filter at 1500 Hz and notch filter at 60 Hz, in a 10-ms window, through insertion phones.

ERPs were recorded, to detect N2 and P3 waves, via electrodes placed on the skull landmarks (Klem et al., 1999). P3 waves are ERP components that are typically linked to general attention sustainability and thought to reflect processes involved in stimulus evaluation or categorization as well as in decision making. N2 waves were used as a mismatch detector here, but they have also been found to reflect executive cognitive control functions and have been used in research on language (Schmitt et al., 2000; Folstein and Van Petten, 2008; Van Dinteren et al. (2014)). P3 and N2 waves were elicited using an oddball paradigm, in which low-probability target items or deviant stimuli (2-kHz tone bursts) were mixed with high-probability non-target (or “standard”) items (1-kHz tone bursts). Tone-burst stimuli at 70 dBnHL were presented monaurally through insertion phones at a rate of 1.10/s during 530 ms, with low-filter 1 Hz (12 dB/octave) and high-pass filter at 100 Hz and notch filter at 60 Hz. There were offered about 300 frequent and rare stimulations, according to the oddball paradigm. The rare stimuli, at the 2-kHz frequency were offered in 20% of presentations and the frequent stimuli, at the frequency of 1-kHz, in 80% of presentations. Potentials were collected from monaural presentations in each ear independently, to allow the analysis of the effect of possible changes in the most peripheral routes on the latencies and amplitudes of cortical auditory potential. The sequence of tones was randomized, with the constraint that 2 target tones were never presented in succession. Subjects were instructed to mentally count the deviant stimuli and the responses were checked at the end of the examination by comparing with the total foreseen deviant stimuli or only signing up the hand when they hear it. When the child had difficulty counting, the evaluator followed the hand signaling coincident with the presentation of the deviant stimuli during the execution of the exam. Both tests were conducted in non-sedated subjects in a comfortable reclining position, utilizing the Navigator (Biologic Systems) coupled to a computer, with silver surface electrodes placed in positions based on the International 10–20 System (Klem et al., 1999): an active electrode in Fz, two reference elements A1 and A2 and a ground electrode in Fpz3 was used (Silva et al., 2010). The potential P1, N1, P2, N2 and P3 were analyzed. Skin impedance was maintained below 5 k Ω , with an inter-electrode variance not greater than 2 k Ω . These limits were periodically checked during data collection.

2.2.3. Auditory processing evaluation (APE)

The model used in this study was based on a validated test with norms for Brazilian children (Pereira and Schochat, 1997), considering the dimensions of decoding, coding and binaural integration; this includes tests, as described below, of DD and SN for *decoding*, LOC for *integration*, PSI/SSI, and SSW in Brazilian Portuguese for

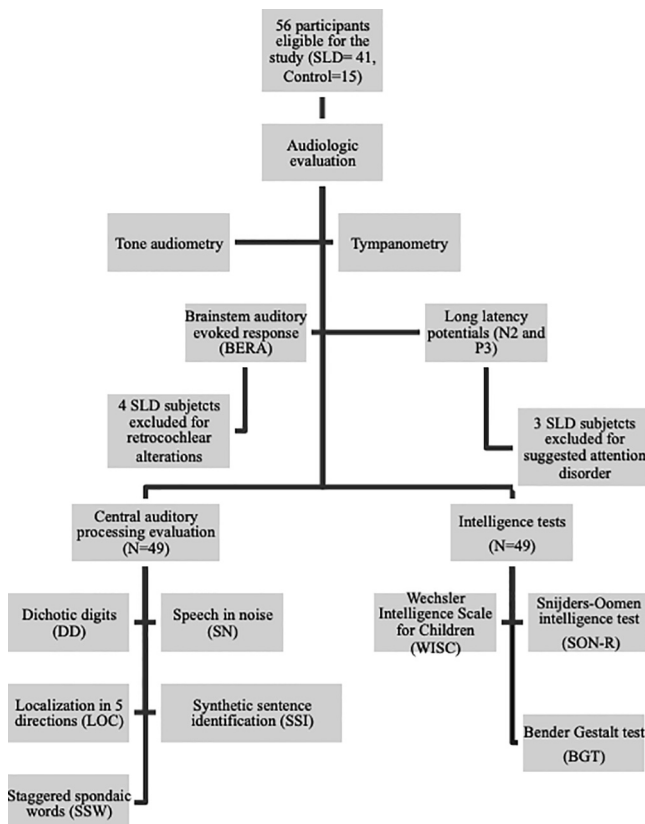


Fig. 1. Procedure flowchart of the study.

coding, using a 2-channel audiometer (Model Beta6000, Betamedical) through TDH39 phones.

1. The DDtest is a list that consists of 80 digits or 20 items, each item consisting of 4 words representing numbers, selected from digits 1 through 9. The test provides for the presentation of 2 digits in each ear simultaneously. The most frequently used test stage is binaural integration. At this stage, the individual is instructed to orally repeat the 4 numbers presented in both ears, regardless of the order of presentation. Correct processing of stimuli in the left ear indicates adequate inter-hemispheric communication, while altered results in both ears suggest functional alterations in the left hemisphere for speech processing. DD makes it possible to evaluate the auditory figure-ground perception ability for verbal sounds, and low performance in this test indicates an impairment of the auditory gnostic process called decoding.
2. The SN test is a repetition of 50 monosyllabic target words (i.e., 2 lists of 25 words each) presented monaurally against background chatter, with a signal-to-noise ratio of +10 dB. Signal and noise can be presented either in the same ear (ipsilateral) or in different ears (contralateral). This test assesses difficulty in understanding speech against background noise, which is one of the most frequent complaints of children with learning disabilities. It evaluates selective and sustained attention skills, auditory closure, and low redundancy speech decoding.
3. The LOC test is performed to seek information about binaural interaction, with the evaluated physiological mechanism being the discrimination of the direction of the sound source. The test consists in observing the child's response to a rattle stimulus located above, behind, in front of, to the right, or to the left of the child's head, while they are sitting in a chair with their eyes closed. The child must indicate the position by hand after opening their eyes. Normal sound localization ability was assumed when at least 4 of the 5 tested directions were indicated correctly. Performance was considered altered when only 3 or less directions were correctly identified (Pereira and Schochat, 1997).
4. To analyze the ability of auditory figure-background and audio-visual association, the PSI test was carried out with the non-literate children and the SSI with children with literacy. In the PSI/SSI test, stimuli consist of 10 sentences, presented simultaneously to a competing message composed by a story. The PSI/SSI test was performed with contralateral competing messages, with a main message/competing message relation of 0 dB/−40 dB, and with ipsilateral competing messages with a main message/competing message relation of 0 dB/−10 dB (Keith, 1977; Bellis, 2011). In PSI, the children should look for and point to the figure, in the panel, that corresponds to the phrase heard in the middle of the competitive story. In SSI, the literate children should look up in a list of 10 numbered sentences and say the number of the phrase they heard, amidst the competitive story. The expected hit level is: 90% in contralateral competing messages, with a main message/competing message relation of 0 dB/−40 dB, and with ipsilateral competing messages with a main message/competing message relation of 0 dB is 80% and −10 dB is 70% (Pereira and Schochat, 1997).
5. The SSW test is a dichotic test composed of 40 items, where each item consists of 4 words that are 2 pairs of paroxysmal disyllables presented either isolated or overlapping. The first word is isolated in 1 ear (left or right), while the second and the third word are presented in both ears, overlapping, and the fourth word is isolated in the ear contralateral which the ear the first word was presented in. The ears are alternated each new item presentation. The participant should repeat what they

heard by following the order of the presentation of the words. This test was performed at an intensity of 50 dB SL (Pinheiro et al., 2010). The physiological mechanism of hearing that is assessed with this test is related to the inhibition of sounds that, although present in the communication environment, are being relatively ignored. This mechanism can also be understood as selective attention. Altered performance in this test suggests an impairment of the auditory gnostic process called coding (Katz and Tillery, 2005).

2.2.4. Intelligence and visuomotor skill assessment

We used the Wechsler Intelligence Scale for Children (WISC), but chose the third version, rather than the fourth; this version is organized into different intelligence quotients (IQs) for verbal (VIQ) and performance areas (PIQ), besides the Full Scale IQ (FSIQ), and presents indexes for Verbal Comprehension (VCI), Perceptual Reasoning (PRI), Processing Speed (PSI), and Freedom from Distractibility (FDI) (Mayes and Calhoun, 2006). Thus, it offers a more refined analysis of verbal and perceptual organization scores. The scale was applied in its entirety, including all subtests (listed in Table 1), and each test score was entered in the general analyses to evaluate strength and weakness profiles (Nyden et al., 2001). WISC indexes and tests were included in all analyses, because they evaluate both verbal and executive skills. In addition to the WISC, we used the Snijders-Oomen Non-verbal Intelligence Test (SON-R test) to correlate with the verbal test to investigate whether testing with oral instructions could underrate intelligence in subjects with APD. The Bender Visual Motor Gestalt Test (BGT) was used to assess perceptual motor skills and perceptual motor development, as it gives an indication of neurological deficits in children (Reynolds, 2007). Test results were scored based on the accuracy and structure of the children's reproductions, and the numbers of mistakes were computed by observing errors as poor integration, perseveration, rotation >45°, and distortion of the visual pattern relative to age, as an indication of a possible delay or neurological disorder in the responses.

2.3. Statistical analysis

Comparisons for group and laterality differences in audiologic measures were conducted using Student's *t*-test on TA thresholds, BERA and ERP latencies, for comparing left and right ears, as well as for performance on verbal and non-verbal intelligence tests. A Spearman bivariate correlation analysis was conducted to investigate interactions between sensorineural variables and WISC, as well as BGT test performance. Results from both groups, with respect to performance in APE tests, were compared with BGT and WISC results, such as IQs, indexes, and tests scores, by using the Mann-Whitney exact test. A multiple linear regression model was used to verify whether the factors TA, APE, ERP, and sociodemographic variables could explain the WISC results to the all sample. All data were analyzed with SPSS V.21. A level of $p < .05$ was considered significant.

3. Results

Firstly, we investigated differences between groups for sociodemographic factors; WISC, SON, and BGT scores; audiologic measures; and APD. The sample performance and group comparison for WISC, SON, and BGT tests, as well as sociodemographic profiles, are described in Table 1. There was no difference between parental (mother and father) education levels. Groups did not differ in age, type of school, parental education and full-scale IQ of verbal (WISC) and non-verbal tests of intelligence (SON). Comparison analyses showed that groups significantly differed, with a disadvantage for the SLD group in terms of school grade ($p = .014$):

Table 1

Mean standard scores for control and specific learning disorder groups, as well as total group results of sociodemographic factors, Wechsler Intelligence Scale for Children cognitive profile, Snijders-Oomen Non-verbal Intelligence Test total Intelligence Quotient and Bender Visual Motor Gestalt Test scores for correct answers.

Sample Description		Groups		Total	p-value
		M ± SD/N° (%)		M ± SD/N° (%)	
		Control (N = 15)	SLD (N = 34)	(N = 49)	
Children School Grade	P1	0	6(17.7%)	6(12.24%)	0.014
	P2	0	5(14.7%)	5 (10.20%)	0.014
	P3	3(20.0%)	4(11.8%)	7 (14.29%)	0.014
	P4	3(20.0%)	7(20.6%)	10 (20.41%)	0.014
	P5	2(13.3%)	7(20.6%)	9(18.37%)	0.014
	≥P6	7(46.7%)	5(14.7%)	12 (24.49%)	0.014
Type of School	Private	12(80.0%)	23(67.6%)	35(71.43%)	0.383
	Public	3(20.0%)	11(32.4%)	14(28.57%)	0.383
Parental Education	Incomplete Primary	0	3(8.8%)	3 (6.12%)	0.151
	Secondary	1(6.7%)	7(20.6%)	8(16.32%)	0.151
	Incomplete Bachelor	0	2(5.9%)	2(4.08%)	0.151
	Bachelor	10(66.7%)	14(41.2%)	24 (48.98%)	0.151
	Graduate	4(26.7%)	8(23.5%)	12(24.49%)	0.151
WISC-III	FSIQ	112.87 ± 9.67	111.50 ± 22.64	111.94 ± 19.35	0.855
	VCI	114.60 ± 9.42	111.22 ± 21.30	112.30 ± 18.31	0.927
	FDI	102.53 ± 8.32	93.72 ± 16.08	96.53 ± 14.58	0.038
	PSI	108.33 ± 9.31	96.13 ± 12.58	100.02 ± 13.00	0.001
	PRI	113.53 ± 11.80	101.31 ± 20.46	105.21 ± 18.91	0.084
	VIQ	114.93 ± 9.48	114.94 ± 21.62	114.94 ± 18.50	0.927
	Similarities	12.67 ± 2.80	11.91 ± 4.82	12.15 ± 4.26	0.435
	Comprehension	13.00 ± 2.10	13.19 ± 4.41	13.13 ± 3.80	0.630
	Vocabulary	12.13 ± 1.77	12.28 ± 3.96	12.23 ± 3.40	0.765
	Digit Span	10.33 ± 2.26	9.41 ± 3.44	9.70 ± 3.12	0.286
	Information	12.27 ± 2.63	10.25 ± 3.70	10.89 ± 3.50	0.078
	Arithmetic	10.79 ± 2.23	8.91 ± 3.25	9.48 ± 3.08	0.047
	Picture Arrangement	9.00 ± 0.00	9.83 ± 4.23	9.51 ± 3.32	0.655
	PIQ	112.27 ± 12.19	113.06 ± 25.44	112.81 ± 21.95	0.706
	Coding	10.73 ± 1.75	8.72 ± 2.29	9.36 ± 2.32	0.005
	Block Design	11.47 ± 2.10	9.56 ± 3.55	10.17 ± 3.26	0.076
	Picture Completion	11.27 ± 1.94	11.53 ± 3.45	11.45 ± 3.03	0.468
	Object Assembly	10.00 ± 2.50	8.54 ± 3.44	9.10 ± 2.77	0.110
	Labyrinth	11.67 ± 1.79	8.26 ± 4.47	9.61 ± 3.99	0.021
	BGT	Integration	0.53 ± 1.13	1.53 ± 1.76	1.22 ± 1.65
Distortion		0.93 ± 1.44	2.79 ± 2.07	2.22 ± 2.07	0.002
Rotation		0.53 ± 1.13	1.71 ± 1.92	1.35 ± 1.79	0.010
Perseveration		0.33 ± 0.90	0.41 ± 0.78	0.39 ± 0.81	0.327
SON Test	FSIQ	92.60 ± 17.21	96.85 ± 13.05	101.00 ± 8.89	0.097

Notes: M ± SD = mean and standard deviation; N° (%) = frequency (percentage); SLD = specific learning disorder; Children School Grade: P1–6 = Primary 1–6 (ages 6–11); WISC-III = Wechsler Intelligence Scale for Children-III; FSIQ = Full Scale Intelligence Quotient; VCI = Verbal Comprehension Index; FDI = Freedom From Distractibility Index; PSI = Processing Speed Index; PRI = Perceptual Reasoning Index; VIQ = Verbal Intelligence Quotient; PIQ = Performance Intelligence Quotient; BGT = Bender Visual Motor Gestalt Test; SON = Snijders-Oomen Non-verbal Intelligence.

32.4% of the participants were retained in initial levels (Primary 1 and 2). There were also disadvantages with respect to the WISC test at FDI and PSI indexes, Arithmetic, Coding and Labyrinth tests ($p \leq 0.047$); and with respect to the BGT test, with the SLD group exhibiting more errors in Integration, Distortion, and Rotation ($p \leq 0.021$).

The whole sample and group auditory performance, as well as the results of audiologic and APE assessments, is presented in Table 2, where group comparison considers laterality, left and right ears, and contra and ipsilateral responses for the PSI/SSI test. Initially, the laterality for these measures was analyzed within groups to verify differences between left and right ears for audiologic assessments and for the APE tests, DD and SSW. Both groups exhibited no within-group difference between ears in terms of auditory threshold and APE tests. Thus, the average auditory threshold for both ears was 8.33 dB (± 4.10) for the control group and 10.49 dB (± 3.44) for the SLD group; these values were used for statistical analysis purposes with WISC and BGT scores. The SLD group showed no between-ear differences in short and long latencies, BERA, or P3/N2. However, the control group exhibited differences;

thus, separate analyses for both ears were performed based on these latencies.

There was no difference between ears for APE tests DD and SSW in both groups, although ears were analyzed separately to investigate the effects of laterality on cognitive and visuomotor performances. The participants of both groups had normal middle-ear function, with type A or type As tympanogram at a 226-Hz probe tone, and normal acoustic reflexes (ipsilateral and contralateral) in both ears. Comparison group analyses revealed significant differences for all APE tests, as well as PSI/SSI-ipsilateral. Overall, the SLD group had significantly lower performance in APE tests and demonstrated longer latencies auditory responses than the control group in all BERA waves ($p = .000$) and at the interpeak intervals WI-III and WI-V. P3/N2 latencies auditory responses were also longer for the SLD group, although these were not significant.

The correlation analyses considered the entire sample between short and long latencies of auditory responses measurements and WISC tests revealed significant interactions between WI and Coding ($r = -0.653$, $p = .029$); between WI-III and Comprehension ($r = -0.671$, $p = .017$) and Labyrinth ($r = -0.698$, $p = .017$); between

Table 2
Mean standard scores for the control and specific learning disorder groups of auditory processing evaluation tests and latencies for sensorineural measures of brainstem evoked response audiometry, as well as long latency potentials (P3 and N2) in the right and left ears.

Audiologic Measures	Laterality		Groups				Total		p-value [*]
			Control		SLD		Mean	SD	
			Mean	SD	Mean	SD			
APE Tests	Right Ear	DD	99.00	1.254	78.65	30.126	86.10	25.81	0.013
		SSW	97.87	1.598	70.96	31.304	80.80	28.02	0.003
	Left Ear	DD	99.00	1.363	77.12	31.878	85.12	27.38	0.000
		SSW	97.00	1.690	71.27	32.048	80.68	28.29	0.000
		PSI/SSI Contralateral	98.93	1.534	88.73	20.983	92.46	17.34	0.001
		PSI/SSI Ipsilateral	95.00	0.000	52.12	25.619	67.80	29.11	0.512
		SN	80.33	36.404	77.77	13.975	78.71	24.23	0.000
LOC	5.00	0.000	4.12	0.971	4.45	0.87	0.002		
BERA Latency/msec	Right Ear	Wave I	1.750	0.774	2.181	0.460	2.026	0.618	0.000
		Wave III	3.446	0.136	4.298	0.513	3.992	0.586	0.000
		Wave V	5.493	0.173	6.119	0.414	5.894	0.459	0.000
		WI I - III	2.297	0.221	2.095	0.210	2.168	0.232	0.020
		WI III -V	1.844	0.029	1.836	0.233	1.839	0.186	0.105
	Left Ear	WI I - V	3.909	0.074	3.956	0.225	3.937	0.180	0.077
		Wave I	1.537	0.050	2.036	0.579	1.852	0.518	0.000
		Wave III	3.417	0.118	4.191	0.957	3.911	0.853	0.000
		Wave V	5.400	0.000	5.896	1.273	5.718	1.040	0.000
		WI I-III	2.379	0.155	2.235	0.144	2.288	0.162	0.012
		WI III-V	1.795	0.072	1.762	0.175	1.77	0.146	0.553
ERP Latency/msec	Right Ear	WI I-V	4.347	0.378	4.026	0.212	4.15	0.328	0.018
		P3	307.17	11.57	328.397	56.097	319.90	44.87	0.881
	Left Ear	N2	252.05	13.93	261.338	68.781	257.00	50.55	0.886
		P3	330.64	7.59	342.037	45.456	337.60	35.95	0.451
		N2	228.72	5.57	249.146	53.433	239.28	39.36	0.813

Notes: * calculated using the paired Student *t*-test; values are expressed as mean \pm standard deviation \pm SD) or frequency (%); SLD = specific learning disorder; APE = auditory processing evaluation; DD = dichotic digits test-double pairs; SSW = staggered spondaic words; PSI/SSI = pediatric/synthetic sentence identification test; SN = speech in noise test; LOC = localization in five directions; BERA = brainstem evoked response audiometry; WI = waves interval; ERP = event-related potential.

WIII-V and Picture Arrangement ($r = -0.661$, $p = .019$) and PIQ ($r = -0.625$, $p = .030$); and between WI-V and Coding ($r = -0.653$, $p = .029$), Vocabulary ($r = -0.619$, $p = .042$), and PSI ($r = -0.654$, $p = .029$). N2 had a negative correlation with WISC Similarities ($r = -0.378$, $p = .043$) and Labyrinth ($r = -0.442$, $p = .021$). Children with higher numbers of errors in the BGT exhibited longer latencies of WI-V ($r = 0.693$, $t(24) = 2.543$, $p = .038$).

Multiple linear regression was used to verify whether the factors TA, ERP, APE performance, and parental education level could explain WISC and BGT performance. We found 11 significant results among all 19 analyzed factors (Table 3). Regression showed that parental education level was a significant predictive indicator of BGT. The WISC, Full-Scale IQ, and Verbal IQ were predicted by PSI/SSI – ipsilateral; Performance IQ was predicted by PSI/SSI-ipsilateral and – contralateral; Freedom from Distractibility was predicted by PSI/SSI-ipsilateral and by P3/N2 right and N2 left ears components. The WISC subtest Digits was predicted by APE test DD in both ears, as well as PSI/SSI-ipsilateral and LOC; Object Assembly by DD in both ears and PSI/SSI-contralateral; Picture Completion by DD left ear and PSI/SSI-ipsilateral; and vocabulary and Information by LOC. Overall BGT was predicted by parental education, DD in both ears, as well as PSI/SSI-ipsilateral. ERP P3 components in the right ear predicted BGT Integration and Rotation; N2 components in the right ear predicted BGT Integration; while N2 components in the left ear predicted BGT Rotation. By merging all BGT categories of errors, we found that longer latencies of P3 in the right ear and N2 in the left ear significantly predicted the lowest full performances of BGT: $F(1, 34) = -0.950$, $p = .016$, $R^2 = 0.83$ and $F(1,34) = 1.094$, $p = .006$, $R^2 = 0.88$, respectively).

In summary, multiple factorial regression showed a significant interaction effect of APE tests and P3/N2 over WISC performance with respect to freedom of distractibility indexes and over performance on the subtests for Digits Span, Picture Completion, Object Assembly, Vocabulary, and Information. The overall trend to make

errors on visuomotor test BGT was predicted by lower parental education, lower performance in APE tests DD and PSI/SSI-ipsilateral, and longer WI-V and P3/N2 latencies, particularly with respect to integration and rotation distortions.

4. Discussion

The results of this study show that individuals with APD have poorer scores on subtests of the performance and Freedom from Distractibility scales, failing specifically in the subtests Arithmetic, Coding, and Labyrinth and demonstrating poorer visuomotor performance; this confirms our hypothesis of an APD cognitive profile and replicates Miller's (2011) findings that cognition may be predicted by speech recognition and listening skills. Alterations in APE performance resulted in stimulus loss and subsequent performance loss.

In an analysis of the sensorineural dimension of the collected data, we found that long latency auditory potentials (N2 and P3) did not differ between groups, and that these predicted the index freedom from distractibility of WISC; this indicates that longer N2-P3 latencies auditory potential were associated with lower index, as expected by the literature confirming the link between these potentials and attention skills (Miller, 2011; Katz and Tillery, 2005). In addition, the absolute latencies of waves I, III and V presented increased latencies in the SLD group, significant only for wave I, but the interpeak latencies were adequate and comparable to the control group. This fact indicates that peripheral influences may be promoting delay at the beginning of neural conduction, but at the moment the potential is initiated with wave I, the neural conduction velocity remains within the expected, indicating absence of neural alteration. (Norrix et al, 2012; Eggermont and Don, 1986). As all children in both groups had a type A curve, leading to conductive changes and normal audiome-

Table 3

Significant results from the multiple linear regression verifying whether the factors parental level of education (higher or not), auditory processing evaluation (presence of disorder; altered or not) and audiologic variables correlate with Wechsler Intelligence Scale for Children subtest performance.

Predictors			Dependent Variables WISC and BGT	B	β	p-value	r^2	95% CI of β
Parental Education			BGT-Integration	-0.178	-1.603	0.001	0.88	-1.777 to -0.580
			BGT-Rotation	-1.405	-1.545	0.010	0.80	-2.389 to -0.421
APE	DECODING	DD Right Ear	Digits	-0.241	-2.190	0.005	0.41	-0.401 to -0.08
			Object Assembly	-0.345	-3.445	0.040	0.49	-0.672 to -0.018
			BGT-Integration	-0.159	-2.701	0.040	0.88	-0.308 to -0.009
		DD Left Ear	Picture Completion	0.127	1.356	0.041	0.46	0.006 to 0.248
			Digits	0.183	1.766	0.012	0.41	0.043 to 0.324
			Object Assembly	0.315	3.136	0.050	0.49	0.000 to 0.629
	CODING	PSI/SSI Contralateral	BGT-integration	0.201	3.383	0.015	0.88	0.047 to 0.354
			Total IQ	0.447	0.419	0.026	0.47	0.057 to 0.836
			Performance IQ	0.478	0.385	0.051	0.41	-0.001 to 0.957
		PSI/SSI Ipsilateral	Picture Completion	0.068	0.456	0.012	0.46	0.016 to 0.119
			Object Assembly	0.087	0.488	0.032	0.49	0.008 to 0.167
			Full scale IQ	-0.333	-0.523	0.007	0.47	-0.570 to -0.096
	INTEGRATION	LOC	Verbal IQ	-0.369	-0.646	0.002	0.42	-0.592 to -0.147
			Performance IQ	-0.377	-0.509	0.013	0.41	-0.668 to -0.085
			Freedom Distractibility Index	-0.407	-1.028	0.046	0.82	-0.807 to -0.008
			Picture Completion	-0.052	-0.590	0.003	0.46	-0.084 to -0.002
			Digits	-0.047	-0.478	0.017	0.41	-0.084 to -0.009
			BGT-Integration	-0.033	-0.816	0.046	0.88	-0.066 to -0.001
ERP	P3 Right Ear	Vocabulary	2.25	0.68	0.009	0.36	0.607 to 3.895	
		Information	2.35	0.621	0.014	0.37	0.519 to 4.181	
		Digits	1.594	0.485	0.044	0.41	0.045 to 3.142	
	N2 Right Ear	FDI	-0.462	-1.516	0.004	0.82	-0.743 to -0.181	
		BGT-Integration	-0.039	-0.975	0.004	0.88	-0.062 to -0.015	
		BGT-Rotation	-0.069	-1.402	0.030	0.80	-0.107 to -0.030	
N2 Left Ear	FDI	0.459	1.853	0.001	0.82	0.239 to 0.679		
	BGT-Integration	-0.024	-0.936	0.014	0.88	-0.042 to -0.006		
	FDI	-0.225	-0.772	0.038	0.82	-0.435 to -0.015		
			BGT-Rotation	0.040	1.084	0.010	0.80	0.012 to 0.068

Notes: β = not standardized coefficient; p-values <0.05 were considered significant; WISC = Wechsler Intelligence Scale for Children; BGT = Bender Visual Motor Gestalt Test; APE = auditory processing evaluation; DD = dichotic digits test-double pairs; PSI/SSI = pediatric/synthetic sentence identification test; IQ = intelligence quotient; LOC = localization in five directions; CI = confidence interval; ERP = event-related potential; FDI: Freedom Distractibility Index.

try, the possibility of subtle changes in internal ear functionality is suggested to justify such a finding.

However, auditory latencies of brainstem and cortical waves were related to poorer visuomotor performance, in this paper, indicating a possible cascade effect of altered/delayed brainstem waves (BERA) over cortical waves (P3/N2). Hence, the altered effect found between P3/N2 and visuomotor tests maybe a result of a peripheral or sensorial error or delay. We found a laterality effect, though it's not clear the underlying mechanism and a specific study must be run to investigate it. Surprisingly, they were also related to tests of perceptual reasoning that measure visual and visuomotor skills, such as Coding, Labyrinth, and Picture Arrangement, thereby lowering PIQ. These tests are associated with executive functions, and we must consider that the longer waves are a measure of maturity of the acoustic nerve, as well as of its integrity and its interaction with visual nerve that cross in at least two structures of the brainstem. Hence, longer latencies, even within the normal reference range, should be investigated in children with SLD, as a neural immaturity marker and as part of follow-up programs.

The analyses of intelligence test performance included all subtests, not only the full and partial IQs and indexes. Earlier research has suggested that profile analysis at the subtest level with corroborating evidence provides specific information that is lost if analyses are based only on composite or factor scores (Nyden et al., 2001). This more specific information may be useful in understanding a child's strengths and weaknesses and in guiding treatment and educational programs. In analyses of general scores and sub-scores, we found that altered APE results generally predicted a lower full-scale IQ; in particular, specific alterations in APE tests performance, such as for DD, PSI/SSI, and LOC, were

predicted to generally lower comprehension abilities and both verbal and executive functions with a highly significant focus on the performance index. In general, normal APE evaluation results were linked to better results with respect to full-scale IQ, verbal, freedom from distractibility, and performance indexes of WISC. Considering the three dimensions of disorders, we concluded that all coding, decoding, and integration disorders affected cognitive performance in this study (Table 3). Notably, the *coding* disorder dimension had broader impact, as it affected full-scale, verbal, and performance IQs, as well as Freedom from Distractibility index. Coding deficit has been linked to inability to apply the rules of language to incoming acoustic information, compound sentences, and complex linguistic messages, as well as inability to sequence, plan, and organize responses to auditory information or instructions, and inability to attach linguistic meaning to phonemic units of speech. Integration deficit is characterized by difficulty in tasks requiring inter-hemispheric transfer (*right hemisphere or corpus callosum*). Symptoms may be confined within a single modality or may be multimodal because the corpus callosum, a structure composed by multimodal fibers. The auditory symptoms may be the primary factor or a single manifestation of multimodal difficulties. In the case of auditory decoding deficits, the primary auditory-specific site of dysfunction is the primary auditory cortex in the language-dominant hemisphere, which implies that reduced intrinsic redundancy is more pronounced in listening situations where extrinsic redundancy is reduced (Bellis, 2011).

In recent decades, distinct and reliable profiles have been reported for several diagnostic groups, by applying the WISC and comparing its versions for these special groups (see review in Mayes and Calhoun, 2006). For instance, children with ADHD,

learning disability (LD), and autism have lower mean scores on the WISC-FDI and PSI than on the VCI, the Perceptual Organization Index, and the Coding versus Symbol Search subtest. Many other special profiles are featured in the manual of the third, fourth, and fifth editions of the WISC. In this study, we observed that children with central auditory disorder and SLD had lower full IQs, verbal IQs, and VCIs than those with only SLD, showing that they may be disadvantaged regarding general intelligence and specifically crystallized intelligence (Cattell, 1987), with lower scores in subtests such as Comprehension, Information, and Similarities. Nonetheless, this disorder also seems to impact skills based on visual and visuomotor processing, and we found that children with central auditory disorder had also lower scores on Object Assembly and Picture Arrangement subtests, as well as on the PIQ. However, very few studies have been performed using these tests in children with APD, and the findings of this study will thus foster further discussions.

The evidence presented here indicates the need for further investigation, and it emphasizes that the appropriate approach for interventions in SLD cases must be multimodal (Haleet al., 2010). In all LD conditions, stimulus perception processes are impaired, which then negatively impacts reading skills, writing skills, learning, and academic achievement. Further studies must encompass, besides a neuropsychological assessment, an auditory evaluation that includes hearing screening, auditory processing screening, and neurophysiological hearing evaluations, as well as visuomotor investigations and neurological assessments of attention deficits (Jerger and Musiek, 2000; Bamouet al., 2001; Banai and Ahissar, 2006; Miller, 2011; Albuquerque et al., 2012). Nonetheless, the interaction effects of educational, familial, socioeconomic, and neuropsychological processes in adolescents and young adults with SLD should not be disregarded (Al-Yagon, 2015) in the search of different factors or conditions that affect overall performance. We suggest that further investigations of the WISC-APD profile can help clinicians and researchers in making a differential diagnosis and in better understanding the impact of APD on learning skills.

In conclusion, the current study suggested that acoustic gnosis is important in explaining neuropsychological outcomes, even for visual spatial processing performance, supporting the hypothesis of perceptual stimulus loss in children with poor auditory processing (Miller, 2011). Learning to read, for instance, depends on at least 2 skills: first, it requires the ability to use spoken language; second, it requires proper visual object perception that is processed in a cross-modal fashion. Suboptimal automatization of the integration of visual analytical skills and language processing may thus lead to learning difficulties (Lachmann et al., 2012). The WISC Verbal IQ and the Full IQ showed the largest correlation with acoustic gnosis. Notably, poor sound localization was correlated with lower vocabulary, information, and digit span; further studies are needed to confirm this interpretation. This study thus reinforces the results of earlier studies (Jerger and Musiek, 2000; Bamouet et al., 2001; Banai and Ahissar, 2006; Miller, 2011; Albuquerque et al., 2012). Moreover, it has been suggested that central auditory processing skills mainly develop until 10 or 12 years of age (Katz, 1992), indicating that the recognition and rehabilitation of this function should happen as early as possible in the life of a child. Symptoms can overlap with many other disorders, because receptive auditory skills are intact, but the ability to act upon incoming auditory information is poor; thus, evidence of an auditory deficit must be confirmed. One limitation of the present study is the small sample size, due to the heterogeneity of confounding factors and other disorders associated with SLD, which resulted in a large number of exclusion criteria. The parents' level of education might influence the quality and quantity of the stimuli that the children are exposed to. We suggest that this variable should be controlled in future studies to ensure more refined statistical analyses.

One relevant aspect of this study regards the composition of the sample for APDs and learning skills, related to the poor auditory follow-up of the children with SLD in our sample. The study began with an audiologic investigation that excluded participants with hearing problems in at least 1 level, which suggests the need for continuous broad auditory follow-ups in children with learning complaints, not only including behavioral audiometry, but as an evaluation of the main auditory pathway. We thus recommend this follow-up for both children with SLD or with APD, should have an audiological or a psychometric assessment depending on the condition. Still, even for children who, despite presenting normal auditory thresholds, have complaints related to difficulty in speech recognition, appear to present more problems in one ear than in the other, despite the presence of symmetric auditory thresholds, as well as for children whose teachers or parents report that they do not seem to be listening, show failures in speech therapy, or difficulties in understanding or speech production.

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Declaration of Competing Interest

None.

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