



Central Auditory Processing and Cognitive Functions in Children

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Abstract

Introduction Nowadays, there is no consensus on whether central auditory processing disorder is a primary or a secondary deficit to other cognitive deficits. A better understanding of the association between cognitive functions and central auditory skills may help elucidate this dilemma.

Objective To investigate possible associations between auditory abilities and cognitive functions in schoolchildren.

Methods Fifty-eight schoolchildren, aged between 8 years and 0 months old and 11 years and 11 months old, who underwent the following tests: masking level difference, gaps in noise, pitch pattern sequence test, dichotic digits test, sustained auditory attention ability test, Wechsler intelligence scale for children – IV, junior Hayling test, five digits test, and behavior rating inventory of executive function.

Results Significant correlations were found between the hearing ability of temporal resolution and executive functions, temporal ordering/sequencing, binaural integration and separation, and sustained auditory attention, operational memory, inhibitory control, and cognitive flexibility; binaural integration was also associated with intelligence. The statistically significant positive correlation found between the ability of binaural interaction and the components of emotional control and behavior regulation of the behavior rating inventory of executive function was unexpected.

Conclusion The associations identified reinforce the complexity of the tasks involved in the evaluation of central auditory processing and the need for multidisciplinary evaluation for the differential diagnosis of auditory processing disorder. Confirmation of the presence or absence of comorbidities between different disorders allows directing the therapeutic behaviors and reducing the impact of possible auditory and/or cognitive deficits in the different daily life situations of children.

Keywords

- ▶ auditory perception
- ▶ attention
- ▶ memory
- ▶ intelligence
- ▶ executive functions

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Introduction

Central auditory processing (CAP) refers to a series of processes and mechanisms that occur from sound being picked up by the outer ear to being interpreted in the auditory cortex, and involves the following skills: sound localization and lateralization; discrimination and recognition of acoustic stimulus differences; temporal processing (resolution, masking, integration, and sequence) and auditory background; and perception of the target stimulus in situations with competitive signals.¹ The mechanisms involved in auditory processing are: binaural interaction, dichotic listening, monaural low redundancy, and temporal processing.²

Binaural interaction is the way the two ears work together for the purpose of locating and lateralizing auditory stimuli, lowering the threshold by masking, detecting acoustic signals in noisy environments, and binaural fusion.³ Dichotic listening consists of the simultaneous presentation of different stimuli in both ears, which causes suppression of ipsilateral auditory pathways and predominance of contralateral auditory pathways.^{4,5} Tests with dichotic listening tasks assess binaural integration skills (ability to hear and understand different stimuli at the same time), binaural separation (when it is possible to ignore one of the stimuli and direct attention to the other simultaneous stimulus), and are sensitive to dysfunctions or injuries of interhemispheric and intrahemispheric connections of the right hemisphere and the left hemisphere.⁶ The monaural low redundancy mechanism occurs when there is degradation of the acoustic signal reducing extrinsic redundancy (phonemic and contextual speech cues) requiring intrinsic redundancy (repetition of acoustic signal analyses along the auditory pathway) to perform auditory closure of missing information allowing understanding of information.⁷ Temporal processing refers to the way nonverbal patterns (rhythm, intonation, emphasis, and intervals) of auditory information are perceived, associated, and interpreted.⁶ It has four subcategories: temporal ordering and sequence, temporal resolution, temporal integration, and temporal masking. There are no clinically viable measures yet to assess integration and temporal masking.⁸

The difficulty in the perception of auditory information along with the central auditory nervous system, evidenced by the poor performance in one or more of the mechanisms mentioned above, characterizes central auditory processing disorder (CAPD). Alterations of higher functions, such as language, attention, and memory, are not included in the definition of CAPD, but may coincide.¹ Therefore, a multidisciplinary assessment may be necessary for differential diagnosis, identifying the primary deficit and the presence of comorbidities.^{1,2,5,9–15}

There is no consensus in the literature about the nature of CAPD, and many discussions have taken place in an attempt to clarify the diagnosis. Some researchers believe that CAPD could only occur when there is a specific auditory deficit and that the tests used to assess CAP show more global responses regarding general intelligence, language comprehension, attention, memory, and executive functions.^{16–21} Other authors, supported by studies of auditory and cognitive neurophysiology, state that considering the specific modality

as a diagnostic criterion is untenable from a neurophysiological point of view, since the central auditory nervous system is complex and responds to stimulation of nonauditory areas.^{1,4,9,10,22,23}

The complexity of the processes that occur in the central auditory nervous system requires knowledge of the auditory and/or cognitive skills required to perform the behavioral tests used to assess CAP. Hearing disability, manifested by the difficulty of understanding auditory information, can leave cognitive, social, and emotional functions vulnerable.²⁴ Functions such as attention, perception, memory, language, and executive functions form human cognition, and acting in an integrated manner, allow individuals to function well in different contexts according to the requirements of the environment.²⁵ The tests developed to evaluate these auditory processes are complex and involve tasks that may require the action of executive functions, such as attention and working memory.²⁶

Executive functions are defined as a set of cognitive processes that guide behavior to achieve goals.^{27–29} There is no consensus on which functions are involved and how their constructs work, but Diamond³⁰ proposes one of the most accepted models, which considers executive functions to have three basic skills: inhibition (self-control and interference control), working memory, and cognitive flexibility. Other skills, such as planning, reasoning, and problem-solving, are complex and emerge from the core. The prefrontal cortex is the main region involved in executive functioning, but it also depends on the activity distributed in different neural circuits,²⁹ with the involvement of various brain areas, including temporal lobe regions. Therefore, changes in regions that affect executive functioning may also affect auditory skills,²² and difficulties in the perception of auditory stimuli may limit the use of an executive function, preventing the generalization of strategic listening behaviors in different situations.²⁶

Studies have been conducted to understand the relationship between CAP and other higher mental functions,^{15,31–41} but there are only a few studies involving the relationship between CAP and executive functions.

Considering that CAPD can coexist with other cognitive and language disorders, the present paper aims to describe the association between auditory skills and cognitive functions to better understand this relationship, which may contribute to health and education, enabling more accurate diagnoses and optimized interventions, reducing the impact of hearing and/or cognitive impairment on the daily life of individuals.

Methodology

The present study was conducted on Centro de Neuropediatria do Hospital de Clínicas (CENEP-HC) da Universidade Federal do Paraná (UFPR) and Centro de Psicologia Aplicada (CPA) da UFPR and was approved by the Research Ethics Committee/UFPR Health Sciences Sector, as Coordinating Center (Opinion 2.675.148) and by the Research Ethics Committee/HC, as a coparticipant institution (Opinion 3.037.057).

The convenience sample consists of 58 children of both genders, aged between 8 years and 0 months old and 11 years and 11 months old, regularly enrolled in the Elementary

School of the Julia Amaral Di Lenna Municipal School ($n = 36$), and/or attended at the outpatient clinic CENEP-HC ($n = 22$), and who are enrolled in elementary school in other Curitiba and metropolitan area municipal public schools.

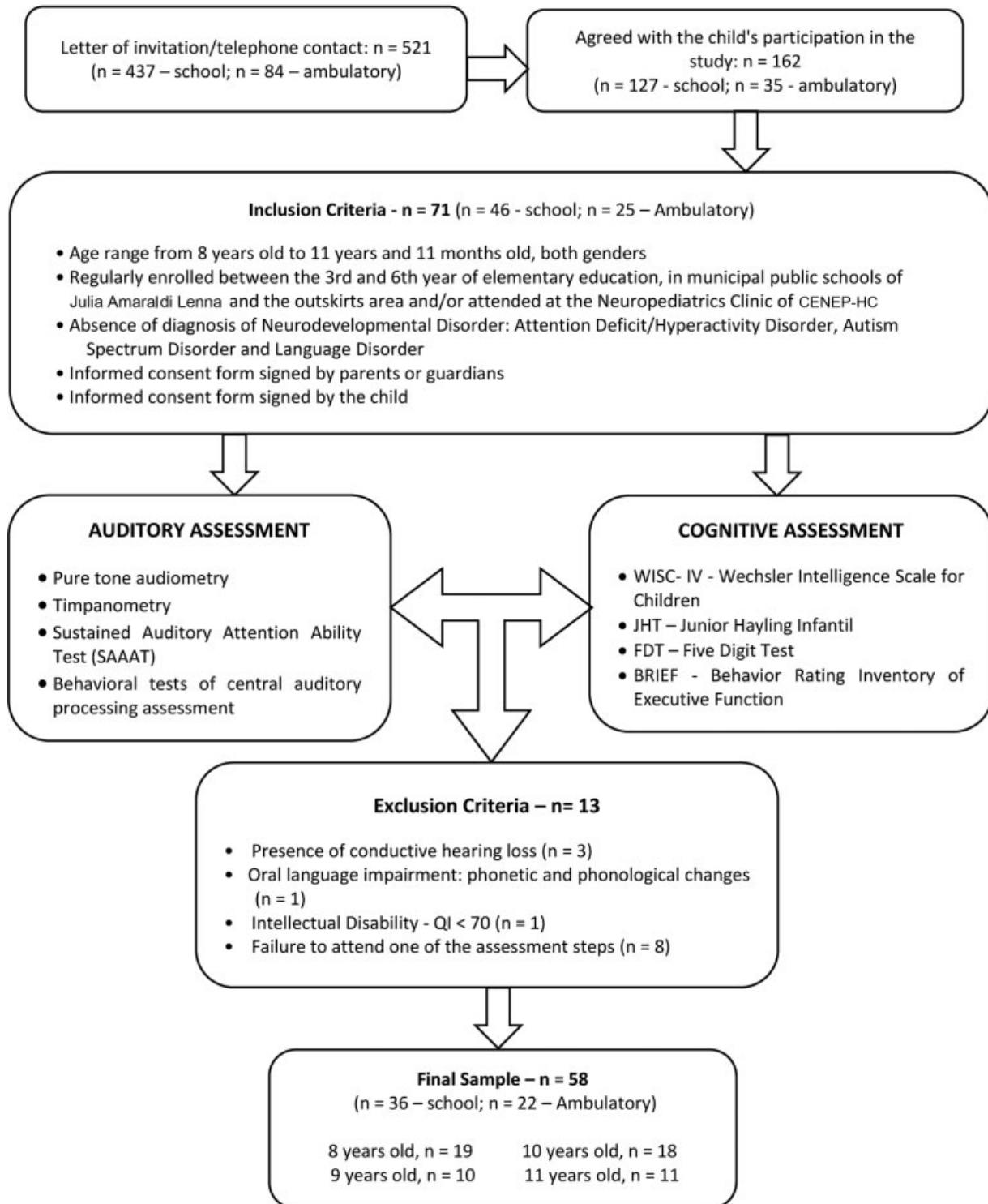
During recruitment, 71 children were included considering the following criteria: regularly enrolled between the 3rd and 6th grade of elementary school, in municipal public schools of Julia Amaral di Lenna ($n = 46$) and/or attended at the clinic of Neuropediatric of CENEP-HC ($n = 25$); absence of diagnosis of neurodevelopmental disorder (attention-deficit / hyperactivity disorder, autistic spectrum disorder and language disorder); free and informed consent form (ICF) signed by parents or guardians; informed consent form signed by the child (ICFC).

According to the exclusion criteria, 13 participants were excluded: conductive hearing loss ($n = 3$); intellectual disability ($IQ < 70$) ($n = 1$); oral language impairment (phonetic/phonological disorders) ($n = 1$); did not complete both assessment steps ($n = 8$).

The final sample consisted of 58 children, 33 males (53.9%) and 25 females (43.1%), with an average age of 9 years and 7 months old (standard deviation [SD] = 1.16). The evaluated children attend between the 3rd and 6th grade of elementary school. The complaint of difficulty in school was reported during anamnesis by 46.6% of the parents or guardians of the children in the sample. ►Fig. 1 demonstrates the data collection process.

The assessment protocol consisted of 2 parts, auditory and cognitive assessment, composed of the following instruments: tonal audiometry threshold hearing thresholds search at frequencies from 250 to 8,000 Hz and speech reception threshold (SRT); tympanometry and acoustic reflex research; masking level difference⁴² (MLD), pure tone (500 Hz) hearing threshold determination in the presence of narrowband noise under two conditions: homophonic – when there is the same phase relationship for tone and noise in both ears (SoNo) – and antiphastic – when noise is in the same phase in both ears, and pure tone is in inverted phase in one ear (SnNo). The intensity used is 45 dBNS, and the result analysis is performed based on the difference between the SoNo and SnNo thresholds. Values > 9 dB are considered appropriate. Gaps in noise⁴³ (GIN), monaural presentation of series with segments of 6 seconds of broadband noise. In each segment, zero to three intervals of silence or gap can occur. The gap duration can be presented in 2, 3, 4, 5, 6, 8, 10, 12, 15, and 20 seconds. The intensity used is 50 dBNS. Values ≤ 8 milliseconds are considered adequate. Pitch pattern sequence⁴⁴ (PPS), 200 milliseconds 3-tone sequences, with intervals of 10 milliseconds between them; between sequences, the interval is 150 milliseconds. The tones are presented binaurally at the frequencies of 880 Hz and 1,122 Hz, representing bass and treble sounds. The sequence of stimuli should be named according to the frequencies shown. The intensity used is 50 dBNS. From the values described by Schochat et al,⁴⁵ the reference values are defined as normality criteria for both ears: 8 years: 47%; 9/10 years: 62%; 11/12 years: 69%; dichotic digits⁴⁶ (DD), presentation of 20 pairs of digits (1 to 9 syllables), 2 simultaneous digits in each ear. Dichotic digits is performed in two steps: binaural

integration, in which the four digits presented must be repeated, and binaural separation, where only the digits presented in the requested ear are repeated. It is performed at an intensity of 50 dBNS. Performance is considered adequate according to the reference values for each age group described in the test manual.⁴⁷ Sustained auditory attention ability test⁴⁸ (SAAAT) is a continuous performance test (CPT), which requires the maintenance of vigilance and the identification of a previously determined target stimulus. It consists of the simultaneous presentation in both ears of a list of 21 recorded monosyllabic words that are repeated and rearranged randomly, forming a list of 100 words, including the 20 occurrences of the target word “no,” presented 6 times without interruption (1 word per second) – totaling 600 monosyllabic words. The individuals should raise their hand each time they hear the target word “no.” The intensity used for the stimulus presentation is 50 dBNS. The reference values by age range described in the test application are used for the analysis of the results. The junior Hayling test⁴⁹ (JHI) (adapted for Brazilian Portuguese), consists of a two-step task, in which the subject must complete sentences in which the last word is missing. In part A, one must use the word that completes the sentence consistently. Part B uses a word that does not have a meaningful relation to the sentence, inhibiting the dominant response, looking for a word that has no relation to the syntactic and semantic context of the sentence. For the classification are considered the percentiles described in the test manual. The five digit test⁵⁰ (FDT), a nonverbal instrument that uses 5 quantities (numbers from 1 to 5) as simple recurrent cognitive units within tasks of increasing difficulty. It consists of four parts: reading, counting, choosing, and toggling; the first two measure automatic and straightforward processes, and the last two measure more complex processes. It allows a brief and straightforward assessment of cognitive processing speed, ability to focus, refocus attention, and ability to deal with interference. For the classification, the percentiles described in the test manual are considered. Wechsler children's intelligence scale⁵¹ (WISC) IV, a clinical instrument that aims to assess children's intellectual capacity and problem-solving process. It provides information on the total intelligence coefficient (IQ) and four indices: verbal comprehension (VCI), perceptual organization (POI), working memory (WMI), and processing speed (PSI). To meet the objectives of the present research, WMI and PSI were analyzed for the evaluation of executive functions, and total IQ for intelligence classification. For classification purposes, composite scores are considered as described in the manual. Behavior rating inventory of executive function⁵² (BRIEF), parent version, a questionnaire consisting of 86 questions that parents must grade from a scale (never, sometimes, consistently) to the frequency of occurrence of problem behavior in the child. It evaluates the behavior of executive functions of children aged between 5 and 18 years old in the family environment. The classification of the results is performed according to the norms of the application manual, and indices > 65 are considered indicative of changes in the evaluated indices. The questionnaire was answered by a parent or guardian who accompanied the child on the day of the assessment. The experimental version provided and authorized by Mello (Universidade

*Central auditory processing and cognitive functions in children***Figure****Fig. 1** Flowchart of the data collection process.

Federal do Estado de São Paulo [UNIFESP, in the Portuguese acronym) was used; Carin, Miranda, and Bueno.⁵²

The children were submitted to the assessment protocol applied individually with a total duration of ~ 3 hours and 30 minutes, divided into 2 days and in different places. The

psychological tests were performed and appraised by a psychologist of the Postgraduate program in psychology of UFPR team.

For the hearing tests, performed in the CENEP-HC, the following equipment was used: a) São Luiz brand acoustic

booth; b) Clinical Beta two-channel audiometer, with headphones TDH-39 and cushion MX-41, coupled to the compact disc (CD) of a DELL computer; c) Interacoustics brand middle ear analyzer, model AZ-7, with TDH-39 earphone, MX-41 cushion, with probe tone 220 Hz at 70 dB; d) CD with recording of MLD tests,⁵³ GIN and PPS (CD purchased directly from the author Frank Musiek),^{54,55} and DD,⁴⁷ f) download of SAAAT test audio file available to registered speech therapists at <http://thaas1.fob.usp.br>. (Sustained Auditory Attention Ability Test - THAAS. Faculdade de Odontologia de Bauru, Universidade de São Paulo. São Paulo. Brazil).

The data were distributed to descriptive analyzes of mean, median, minimum values, maximum values, SD, and frequency analyzes. The use of the Shapiro-Wilk test indicated that some variables are not standard. Therefore, the association between hearing tests and cognitive tests was verified with the Spearman correlation test. The data were analyzed using IBM SPSS Statistics for Windows, version 22.0 (IBM Corp. Armonk, NY, USA).⁵⁶ The significance level of 0.05 was set to determine whether the correlation between variables is significant.

Results

The values obtained in the hearing tests with the general sample and with the participants grouped by age group are described in ►Table 1. Data are presented according to the measurement used for each test: MLD, decibel (dB); GIN, milliseconds (ms), PPS, and DD hit percentage (%).

When analyzing ►Table 1, the difference between the minimum and maximum values in PPS and DD is verified, both in the task of binaural integration and binaural separation, demonstrating the great variability of children's performance in these tests, regardless of age. One participant (10 years old) failed to answer the MLD test adequately, and another participant (8 years old) failed to respond to the GIN. Both participants had difficulty understanding the tests, presenting random answers that could not be considered.

The hearing tests are classified according to the reference values described for each test, and 63.2% of the students presented an adequate performance in the MLD test, and 89.5% in the GIN test. The PPS was the test with the most significant number of underperforming participants (72.4%). In DD, the left ear performed worse in 36.2% of participants in the binaural integration task and in 31% in the binaural separation task.

The auditory skills evaluated were appropriate to the age group in 22.4% of the participants. For classification purposes, the students who presented underperformance for the age group in ≥ 2 hearing tests (58.6%) were considered as having CAPD. When the change was identified in only 1 test, it was classified as evidence of CAPD (19%).

The data that characterize cognitive performance are presented in ►Table 2, with information from the general sample, and in ►Table 3, with the participants grouped by age. It is observed that the median of the participants in the total IQ of the WISC-IV test was 101 points, with the most significant difference in performance in the 10-year-old participants (44 points between the minimum and maximum value), and the lowest in the 11-year-old age group (29 points). In the SAAAT test, the total number of errors varied between 2 and 70 errors, mainly in the age groups of 8 and 9 years old. In the JHT, the variability in response time, especially in part B of the test, was also abundant in all age groups, with time differences between 18 and 150 seconds. In the FDT, the participants took more time to perform the flexibility tasks, with time varying between 11 and 109 seconds; in the age group of 11 years old, the participants had faster responses with a median of 24 seconds. The BRIEF responses indicate T scores with a median of ~ 55 points on all items assessed. The number of participants in the BRIEF test is lower ($n = 52$), as 3 parents did not answer the questionnaire, and 3 questionnaires were excluded from the sample due to a high rate of inconsistency and negative responses.

Regarding the classification in cognitive tests, it is evident that ~ 90% of the participants have a mean score for the

Table 1 Performance of students in hearing tests in the general sample and by age group

Variable		MLD (dB)	GIN (ms)		PPS (%)	DD Integration (%)		DD Separation (%)	
			RE	LE		RE	LE	RE	LE
General sample ($n = 58$)	median	10	5	6	33	95	92	92	91
	min/max	4/14	4/15	4/15	10/86	50/100	40/100	35/100	47/100
8 years old ($n = 18$)	median	10	5	6	30	92	87	90	85
	min/max	6/12	4/10	4/10	10/63	50/100	40/97	50/100	57/100
9 years old ($n = 10$)	median	11	6	6	30	95	86	90	85
	min/max	6/14	5/10	5/12	20/83	62/100	62/100	35/97	47/100
10 years old ($n = 18$)	median	8	5	5	33	97	97	95	93
	min/max	4/12	4/15	4/15	16/80	72/100	65/100	50/100	67/100
11 years old ($n = 11$)	median	10	5	6	46	100	97	92	92
	min/max	6/14	4/8	4/6	23/86	90/100	85/100	67/100	77/100

Abbreviations: dB, decibel; DD, digit dichotic; GIN, gaps in noise; LE, left ear; max, maximum; min, minimum; MLD, masking level difference test; ms, milliseconds; n, number; PPS, pitch pattern sequence; RE, right ear.

Table 2 Performance of students in the instruments that assess cognitive functions, general sample ($n = 58$)

	Variable	n	Minimum	Maximum	Median
WISC-IV	VCI	58	82	138	104
	POI	58	75	130	103
	WMI	58	71	123	97
	PSI	58	74	118	97
	IQ	58	80	124	101
SAAAT	Total Errors	58	2	70	17
	DS	58	-2	11	2
JHT	B Part	58	18	150	38
	Error Category	58	3	27	12
FDT	Inhibition	58	11	88	38
	Flexibility	58	11	109	43
BRIEF	Behavior Regulation	52	42	77	54
	Metacognition	52	33	80	56
	Global Executive Composition	52	37	77	56

Abbreviations: BRIEF, behavior rating inventory of executive function; DS, decreasing surveillance; FDT, five digit test; JHT, junior Hayling test; n, number; POI, perceptual organization index; PSI, processing speed index; SAAAT, sustained auditory attention ability test; TIQ, total intelligence quotient; VCI, verbal comprehension index; WISC-IV, Wechsler intelligence scale for children; WMI, working memory index.

Table 3 Performance of students in the instruments that assess cognitive functions by age group

Variable	8 years old			9 years old			10 years old			11 years old		
	n	min/max	med	n	min/max	med	n	min/max	med	n	min/max	med
WISC-IV												
VCI	19	82/128	104	10	90/138	108	18	82/121	102	11	91/113	104
POI	19	86/126	102	10	90/118	107	18	75/130	101	11	79/126	108
WMI	19	77/123	94	10	74/106	97	18	71/118	97	11	85/118	100
PSI	19	83/115	97	10	86/100	95	18	80/115	95	11	74/118	100
IQ	19	83/119	102	10	84/122	103	18	80/124	99	11	90/119	98
SAAAT												
TE	19	5/70	23	10	11/55	17	18	3/35	15	11	2/35	10
DS	19	1/7	3	10	0/7	3	18	-2/6	3	11	-1/11	0
JHT												
B Part	19	18/150	56	10	27/123	37	18	18/134	40	11	23/108	38
Error Categ.	19	4/25	12	10	3/26	12	18	3/19	9	11	3/27	14
FDT												
Inhib.	19	11/88	25	10	26/55	43	18	13/62	31	11	21/69	35
Flex.	19	37/109	43	10	22/65	51	18	11/92	40	11	14/44	24
BRIEF												
BR	18	42/77	55	9	44/74	54	16	42/72	49	9	58/67	59
Metacog.	18	33/80	54	9	46/70	53	16	39/75	52	9	41/76	57
GEC	18	33/77	55	9	46/70	56	16	40/72	49	9	42/74	60

Abbreviations: BR, behavior regulation; BRIEF, behavior rating inventory of executive function; DS, decreasing surveillance; Error categ., error category; FDT, five digit test; Flex., flexibility; GEC, global executive composition; Inhib., Inhibition; JHT, junior Hayling test; max, maximum; med, median; Metacog., metacognition; min, minimum; n, number; POI, perceptual organization index; PSI, processing speed index; TE, total errors; SAAAT, sustained auditory attention ability test; TIQ, total intelligence quotient; VCI, verbal comprehension index; WISC-IV, Wechsler intelligence scale for children; WMI, working memory Index.

indexes evaluated in the WISC-IV, and the WMI presented the most significant number of participants with inferior performance (5.2%), and the POI with superior performance (10.3%). Not borderline or much higher scores were evidenced in this test. In the JHT test, ~ 30% of the students presented a borderline performance in all indexes evaluated in the test, mainly in part B (32.8%) and in the error category (37.9%). The data obtained in the FDT test show that 60.3 and 44.8% of students had, respectively, percentiles of cognitive flexibility and inhibition, with performance classified as average. The percentiles obtained for inhibition were classified as borderline in 22.4% of the participants and as lower in 27.6%. For flexibility, the rating was 8.6 and 19%, respectively. In the SAAAT test, the total errors were adequate in 75.9%, and the decrease in vigilance in 96.6% of the students. Among the types of errors, inattention was observed in 44.8% of participants and impulsiveness in 20.7%. The classification in the BRIEF indicates that ~ 70 to 88% of the students do not present difficulties in the executive functions investigated in the inventory, according to their parents' perception. However, the data show that ~ 30% of the students have difficulty in working memory.

► **Table 4** shows the estimated correlation measures between each of the variables for the entire sample, and ► **Table 5** shows the study performed according to the age group. In the estimation of the correlations, the following scores of each auditory test were used: MLD, dB; GIN, ms; PPS and DD, percentage of correct answers. Percentile scores for the WISC-IV, JHT and FDT indexes, gross scores for SAAAT and T score indexes for BRIEF were considered for instruments that assess cognitive functions.

► **Tables 4** and **5** show the following correlations between auditory skills and cognitive functions: binaural interaction (MLD) and executive functions (BRIEF); temporal resolution (GIN), processing speed (WISC-IV), inhibitory control (JHT and BRIEF) and planning (BRIEF); temporal ordering/sequence (PPS), working memory (WISC-IV and BRIEF), sustained auditory attention (SAAAT), inhibitory control (JHT), cognitive flexibility (FDT) and metacognition (BRIEF); binaural integration (DD), intelligence (WISC-IV), sustained auditory attention (SAAAT), inhibitory control (JHT and FDT) and cognitive flexibility (FDT); binaural separation (DD), sustained auditory attention (SAAAT), cognitive flexibility (FDT) and inhibitory control (FDT).

Table 4 Correlation between behavioral tests that assess central auditory processing and cognitive function tests in schoolchildren

	Variable	MLD	GIN		PPS	DD - Integration		DD - Separation	
			RE	LE		RE	LE	RE	LE
WISC-IV	VCI	-0.058	-0.217	- 0.054	0.200	0.272*	0.142	-0.132	-0.099
	POI	-0.033	-0.063	- 0.022	0.179	0.393**	0.198	0.094	0.026
	WMI	0.048	-0.172	- 0.050	0.337*	0.407**	0.159	0.178	0.105
	PSI	0.098	-0.262*	0.044	0.007	0.213	0.153	0.030	-0.004
	IQ	-0.006	-0.233	- 0.013	0.235	0.424**	0.220	0.067	0.011
SAAAT	Total Errors	-0.072	-0.030	0.032	-0.513**	-0.259*	-0.363**	-0.381**	-0.299*
	Inattention	-0.043	-0.106	- 0.009	-0.482**	-0.260*	-0.314*	-0.271*	-0.258
	Impulsiveness	-0.041	0.123	0.008	- 0.297*	-0.067	-0.157	-0.446**	-0.263*
JHT	B Part - TE	-0.098	-0.086	- 0.070	0.023	0.202	0.272*	-0.075	-0.059
	TB / TA	-0.103	-0.193	-0.352**	- 0.001	0.153	0.210	-0.154	-0.087
	Error Category	0.123	-0.157	- 0.141	0.293*	0.311*	0.324*	0.181	0.175
FDT	Inhibition	0.066	0.136	0.035	0.214	0.347**	0.196	0.299*	0.054
	Flexibility	0.152	0.048	0.008	0.383**	0.338**	0.226	0.432**	0.137
BRIEF	Inhibition	0.257	0.012	0.359**	- 0.136	-0.077	-0.089	-0.056	-0.107
	EC	0.358*	0.017	0.202	- 0.134	-0.037	-0.018	0.056	0.029
	BR	0.337*	0.000	0.253	- 0.163	-0.057	-0.055	-0.010	-0.057
	WM	0.091	-0.022	0.156	- 0.341*	-0.256	-0.215	-0.081	-0.161
	Planning	0.098	0.040	0.289*	- 0.260	-0.180	-0.129	-0.078	0.057
	Metacognition	0.074	0.050	0.253	- 0.313*	-0.182	-0.138	-0.101	-0.079
	GEC	0.215	0.000	0.269	- 0.256	-0.117	-0.082	-0.031	-0.041

Abbreviations: BR, behavior regulation; BRIEF, behavior rating inventory of executive function; DD, digit dichotic; EC, emotional control; FDT, five digit test; GEC, global executive composition; GIN, gaps in noise; JHT, junior Hayling test; LE, left ear; MLD, masking level difference test; POI, perceptual organization index; PPS, pitch pattern sequence; PSI, processing speed index; RE, right ear; SAAAT, sustained auditory attention ability test; TA, time part A; TB, time part B; TE, total errors; TIQ, total intelligence quotient; VCI, verbal comprehension index; WISC-IV, Wechsler intelligence scale for children; WM, working memory; WMI, working memory index.

Note: * $p \leq 0.05$; ** $p \leq 0.01$.

Table 5 Correlation between behavioral tests that assess central auditory processing and cognitive function tests in schoolchildren by age group

Variable		MLD	GIN		PPS	DD - Integration		DD - Separation	
			RE	LE		RE	LE	RE	LE
8 years old	WISC-IV								
	POI	-0.276	0.170	0.251	0.095	0.496*	0.354	0.205	0.337
	WMI	0.064	-0.045	0.103	0.209	0.523*	0.106	0.329	0.014
	PSI	0.466*	-0.128	0.225	- 0.037	0.057	- 0.146	0.382	0.001
	IQ	-0.043	0.006	0.187	0.148	0.531*	0.266	0.353	0.195
	SAAAT								
	Total errors	-0.090	0.226	0.128	- 0.350	0.018	-0.492*	-0.086	- 0.333
	Impulsiveness	-0.333	0.204	0.061	-0.710**	- 0.306	-0.489*	-0.704**	- 0.423
	JHT								
	B Part - TE	0.055	-0.269	- 0.065	0.158	0.189	0.490*	0.038	0.192
	Error Category	0.324	-0.117	- 0.161	0.462*	0.141	0.562*	0.318	0.267
	FDT								
	Flexibility	0.573*	-0.318	- 0.278	0.215	0.260	0.199	0.372	0.016
	BRIEF								
	WM	0.520*	-0.082	0.124	- 0.003	0.088	0.102	0.397	0.191
9 years old	Total errors	0.147	0.271	0.440	-0.635*	- 0.568	-0.706*	-0.488	-0.466
	FDT								
	Flexibility	0.147	-0.065	- 0.141	0.620	0.634*	0.900**	0.729*	0.400
	BRIEF								
	Inhibition	0.478	0.214	0.155	- 0.067	- 0.311	- 0.120	- 0.360	- 0.867**
	BR	0.751*	-0.100	0.309	- 0.313	- 0.259	- 0.072	- 0.102	- 0.383
	Planning	0.189	0.365	0.543	-0.830*	-0.752*	- 0.380	- 0.610	- 0.151
10 years old	PSI	-0.038	-0.566*	- 0.224	- 0.011	0.394	0.478*	0.048	0.040
	IQ	-0.058	-0.364	- 0.027	0.430	0.502*	0.459	0.230	0.194
	SAAAT								
	Total errors	-0.231	-0.184	- 0.254	-0.520*	- 0.067	- 0.145	- 0.372	- 0.205
	Inattention	-0.214	-0.098	- 0.211	-0.614**	- 0.165	- 0.147	- 0.420	- 0.358
	JHT								
	TB/TA	-0.376	-0.492*	-0.612**	- 0.201	0.067	0.299	- 0.278	- 0.305
	Error Category	-0.436	-0.434	- 0.346	0.348	0.374	0.534*	0.118	0.318
	FDT								
	Inhibition	0.175	0.187	0.367	0.596**	0.470*	0.244	0.599**	0.258
	Flexibility	0.216	0.225	0.272	0.551*	0.415	0.053	0.664**	0.259
	BRIEF								
	WM	-0.298	-0.343	- 0.358	-0.632**	- 0.241	- 0.006	-0.508*	- 0.355
11 years old	POI	0.360	-0.216	- 0.351	- 0.189	0.431	0.233	- 0.441	- 0.751**
	IQ	0.265	-0.101	- 0.133	0.304	0.390	0.030	- 0.376	- 0.614*
	JHT								
	B Part - TE	0.028	0.319	0.091	- 0.179	0.129	- 0.303	-0.792**	- 0.731*
	BRIEF								
	Inhibition	0.503	-0.004	0.704*	- 0.197	- 0.111	- 0.043	0.403	0.225
	EC	0.159	0.159	0.713*	- 0.577	- 0.258	0.047	0.324	0.191

(Continued)

Table 5 (Continued)

Variable		MLD	GIN		PPS	DD - Integration		DD - Separation	
			RE	LE		RE	LE	RE	LE
	BR	0.159	0.159	0.681*	- 0.611	- 0.157	0.158	0.277	0.178
	Metacognition	-0.291	0.388	0.389	-0.727*	- 0.438	- 0.009	0.189	0.004
	GEC	-0.053	0.309	0.519	-0.774*	- 0.253	0.141	0.227	0.085

Abbreviations: BR, behavior regulation; BRIEF, behavior rating inventory of executive function; DD, digit dichotic; EC, emotional control; FDT, five digit test; GEC, global executive composition; GIN, gaps in noise; IQ, total intelligence quotient; JHT, junior Hayling test; LE, left ear; MLD, masking level difference test; POI, perceptual organization index; PPS, pitch pattern sequence; PSI, processing speed index; RE, right ear; SAAAT, sustained auditory attention ability test; TA, time part A; TB, time part B; TE, total errors; VCI, verbal comprehension index; WISC-IV, Wechsler intelligence scale for children; WM, working memory; WMI, working memory index.

Note: * $p \leq 0.05$; ** $p \leq 0.01$.

Due to the different scoring criteria used in the hearing and cognitive tests, negative correlations were expected. Some tests indicate better performance when their rates are low and others when their rates are high. As in the negative correlation found between PPS and SAAAT ($p = -0.513$; $p < 0.001$), indicating the association of the occurrence of the lowest number of errors in the SAAAT subtests with the highest number of correct answers in the PPS. However, the positive correlation identified between MLD and BRIEF indicates that when there is a better perception of the difference in the level of masking in MLD, there are higher rates of emotional control and behavior regulation. High levels in BRIEF suggest the inefficiency of the executive functions.

Discussion

In the last decades, many debates have been taking place among researchers about the interference of cognitive performance in hearing tests,^{1,4,10,16–18,20–22,57} and there is a growing number of studies that seek to understand the association between these functions, with memory and attention functions being the most studied.^{32–34,36,39–41}

The present research aims to verify the possible associations between auditory skills (binaural interaction, temporal resolution, temporal ordering and sequence, binaural integration and binaural separation) and cognitive functions (intelligence, sustained auditory attention, working memory, inhibitory control, and flexibility) in schoolchildren.

Statistical analyses demonstrate the moderate association between sustained auditory attention and auditory skills of temporal order/sequence, integration, and binaural separation, corroborating with the data obtained in other studies that related different CPTs that evaluate sustained auditory and/or visual attention and DD,^{32,33,35,39,41} and also with other auditory tests, such as Staggered Spondaic Word (SSW) that was not used in this study.³⁴ However, Riccio et al.³⁷ and Stavrinou et al.⁴⁰ did not find this correlation. In the present research, as in other studies,^{33,35,39–41} no associations were identified between sustained auditory attention and the MLD and GIN tests. Sustained auditory attention ability showed stronger and more significant correlations with hearing tests than the other correlations. This result is

essential, and difficulties of sustained hearing attention should be considered during the application of hearing tests that evaluate CAP.

The temporal resolution hearing ability evaluated using GIN shows a significant correlation with executive functions: inhibitory control, processing speed, and planning. The task required in GIN requires the subject to respond to interruptions that occur within seconds during a continuous stimulus of white noise. The hypothesis for this association with the inhibitory control function, which was the most statistically significant correlation, is the need to control the impulse to respond to the stimulus even when there is no interval, waiting for stimulus interruption to occur. Self-control is an aspect of inhibitory control in which it is necessary to resist stimuli (external or internal) in order not to act impulsively or prematurely.³⁰ Processing speed and planning may also be required in the task, as stimulus interruption may not occur, or may occur between 1 and 3 times with each presentation, with brief time intervals (2 to 20 seconds), requiring quick and planned responses. The literature does not report similar analyzes involving these tests, which makes it impossible to compare these findings. Studies using the GIN test have made associations with auditory and/or visual attention, as previously reported, and some studies have found possible associations with intelligence using tests that assess non-verbal IQ^{33,35,41} but found no significant correlations.

The ordering ability/temporal sequence evaluated with the task of naming the PPS, in addition to presenting the association with sustained auditory attention, demonstrated association with working memory, cognitive flexibility and inhibitory control evidenced in correlation with phrase categorization errors in the JHT, that is, by evocation patterns and strategies used to inhibit automatic response during the test.⁴⁷ Such associations may be justified by the presence of three stimuli that differ in frequency patterns, which must be memorized and associated with acute/severe concepts (requiring activation of previously stored information recall areas for subsequent naming).³⁴ Cognitive flexibility that involves shifting or shifting the focus of information, action, or thought processing to suit environmental requirements,^{27,29,30,58,59} is also required, since the sequence of stimuli presented in the PPS changes with each presentation.

The data found in the present study also show the statistically significant correlation between working memory and dichotic listening (DD). Understanding that short-term memory involves the temporary storage of information, while working memory implies a combination of storage and manipulation, in the presence of two or more simultaneous stimuli, the participation of the central executive component, which acts as a data supervisor, is required.⁶⁰ Thus, it is inferred that the task required in DD, dichotic listening, involves both types of memory since two stimuli are presented simultaneously in each ear, requiring the central executive component's participation in the maintenance of these stimuli so that they can be repeated accordingly. Maerlender et al.⁶¹ found a strong association between DD and short-term memory, and a more modest association with working memory, reinforcing this hypothesis. Other studies also point to associations between working memory and hearing skills, although using different tests to assess working memory, having found significant correlations with DD,^{31,32} DD and PPS,^{39,41,62} PPS and SSW.³⁴ Murphy et al.³⁵ did not find significant associations between temporal processing tests (PPS and GIN) and working memory tests.

In addition to WMI, other associations were identified between DD and intelligence indexes measured with WISC-IV, such as total IQ, POI, and VCI. Correlations are significant only for the right ear binaural integration task. The advantage of the right ear is because hemispheric areas of language expertise in most individuals are in the left hemisphere,⁶³ and the functions required for the tasks involved in determining indices also involve the left hemisphere, which may justify the correlation found. Gyldenkerne et al.³³ and Tomlin et al.⁴¹ found significant correlations between left ear dichotic listening tasks in DD and nonverbal IQ tests. Other researches did not identify associations between nonverbal IQ and hearing skills.^{32,35,39} Weihing et al.⁶⁴ found significant correlations between PPS and total WISC-IV IQ, but found no association with other WISC-IV indices. This association between WISC-IV, PPS, DD, and total IQ was also observed by Brenneman et al.,³¹ who, by including individuals with language and/or cognitive deficits, identified a higher degree of association also with other WISC-IV indices, such as perceptual organization and working memory.

The DD was also associated with inhibitory control and cognitive flexibility. In the executive function model described by Diamond,³⁰ inhibitory control involves self-regulation and interference control (selective attention), which may justify the findings, since the tasks involved in DD require divided attention (when repeating the four stimuli; two on each side) and directed attention (by repeating only the two stimuli presented in the right ear and then those in the left ear). Stavrinou et al.⁴⁰ found significant correlations between tests that evaluate divided auditory attention and DD, and recommend caution when using and analyzing this test in the CAP assessment battery due to the interference of attentional aspects evidenced in the results found in the research.

The positive and significant correlation evidenced between MLD, emotional control, and behavior regulation

(BRIEF) was unexpected, since it indicates that better responses are expected in MLD when there are higher levels of emotional control and behavior regulation in the inventory, indicating alteration of these components. Considering that emotional control is related to the impact of executive function problems on emotional expression as the individual controls his emotional responses, and that behavior regulation is also related to emotional modulation through appropriate inhibitory control,⁶⁵ it can be inferred that the task required in performing MLD may not require these functions. Although the consulted literature did not show studies using this correlation, studies conducted with MLD associated with other cognitive functions, such as intelligence, attention, and memory, did not find significant correlations,^{33,39,41} showing that this test seems to suffer little interference from the cognitive functions. Further studies are needed for a better understanding of this association.

There is a growing body of literature aimed at understanding the nature of CAPD, but most studies are conducted with relatively small samples. The exception is the work of Moore et al.,⁵⁷ who conducted a study of 1,469 schoolchildren aged between 6 and 11 years old with normal hearing who were randomly selected from schools in different regions of the United Kingdom. The results showed significant correlations between cognitive tests and tests that assess central auditory functions, and the conclusion was that CAPD is primarily a problem of attention, as poor performance in hearing tests was associated with a generalized attention deficit. However, the researchers used an unusual battery of tests to evaluate core auditory functions (frequency discrimination, backward masking, simultaneous masking, speech in noise testing), which precludes generalizing these results with other auditory tests that may require less attention.³³

Considering the results of the present study, it is possible to state that cognitive functions, especially attention and executive functions (working memory, inhibitory control, and cognitive flexibility), are related to some tests that assess central auditory functions and may interfere with the performance of individuals during these tests. Stavrinou et al.⁴⁰ suggest that the CAPD diagnostic criteria need to be reconsidered as they do not include cognitive diagnostic measures. Despite the small sample and weak to moderate associations, the data from the present research reinforce this statement and the recommendation of multidisciplinary assessment in the assessment of CAPD for differential diagnosis among other neurodevelopmental disorders, identifying the presence or absence of comorbidities.^{1,2,5,9-15} Research with larger samples and the use of different instruments to investigate cognition, especially executive functions, is necessary, since the literature is still scarce on the subject.

Conclusion

The associations evidenced in the present study between auditory skills and cognitive functions, although weak to moderate, notably demonstrate that the isolated interpretation of CAP tests can be difficult, since the interference of

cognitive functions, especially sustained auditory attention and hearing impairments, is susceptible. Executive functions (working memory, inhibitory control, and cognitive flexibility) had the strongest correlations with the different hearing tests used. Thus, caution is suggested when interpreting the data obtained in the CAP assessment tests, considering the possible interferences of cognitive functioning.

Further research is needed to better understand the practical implications of the unexpected associations between binaural interaction auditory ability and emotional component executive functions (emotional control and behavior regulation), since no similar studies were found in the literature.

The results of the present study reinforce the need for multidisciplinary assessment, with an investigation of cognitive aspects, to better understand the hearing difficulties evidenced in the CAP tests, allowing the differential diagnosis, the optimization of the therapeutic intervention and the reduction of the impact of hearing deficits and/or cognitive disorders in schoolchildren.

Conflict of Interests

The authors have no conflict of interests to declare.

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