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ASSESSMENT OF LEARNING DISORDER USING THE FREQUENCY FOLLOWING RESPONSE: SYSTEMATIC REVIEW

Contributions:
A Study design/planning
B Data collection/entry
C Data analysis/statistics
D Data interpretation
E Preparation of manuscript
F Literature analysis/search
G Funds collection

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Abstract

Introduction: There seems to be a relationship between learning disorders and changes in auditory skills which can cause short, medium, and long term damage in an individual's life. An early diagnosis can contribute to the treatment of these patients. The frequency following response (FFR) is an objective electrophysiological test for investigating hearing loss related to the coding of speech sounds and has the potential to contribute to diagnoses.

Objective: From the literature to assess the correlation of learning disorders with impaired hearing function in terms of the frequency following response (FFR).

Data synthesis: A systematic literature review was performed using the Scielo, LILACS, Cochrane, and PubMed databases. The database search used filters related to species (human), language (English), and publication year (2009 to 2019). 272 articles were selected from the databases, but only 15 met the inclusion criteria previously established. All studies found a significant relationship between learning disorders and FFR test findings.

Conclusion: It is concluded that there is a correlation between FFR responses in learning disorders via impaired perception of speech sounds. Because FFR is an objective, fast, and effective procedure that does not require the patient's conscious participation, it appears to be an important tool in the early diagnosis of these changes.

Key words: assessment • electrophysiology • auditory • speech perception • learning disorder

OCENA ZABURZEŃ UCZENIA SIĘ ZA POMOCĄ ODPOWIEDZI NAŚLADUJĄCYCH CZĘSTOTLIWOŚĆ: PRZEGLĄD SYSTEMATYCZNY

Streszczenie

Wprowadzenie: Istnieje związek między zaburzeniami uczenia się a zmianami w umiejętnościach słuchowych, które mogą powodować krótko-, średnio- i długoterminowe szkody w życiu pacjenta. Dlatego ważna jest tutaj wczesna diagnoza i jak najszybsze objęcie takich osób opieką medyczną. Odpowiedzi naśladujące częstotliwość (FFR) są obiektywnym badaniem elektrofizjologicznym służącym do badania i diagnozy niedosłuchu związanego z kodowaniem dźwięków mowy. W artykule dokonano oceny korelacji pomiędzy zaburzeniami uczenia się a ubytkami słuchu, opierając się na wynikach FFR dostępnych w literaturze.

Synteza danych: Systematyczny przegląd literatury został wykonany przy użyciu baz: Scielo, LILACS, Cochrane i PubMed, stosując następujące filtry: gatunek (człowiek), język (angielski), rok publikacji (2009 do 2019). Wybrano 272 artykuły, ale tylko 15 spełniało wcześniej ustalone kryteria włączenia. Wszystkie badania wskazywały na istotny związek między zaburzeniami uczenia się a wynikami testu FFR.

Wniosek: Istnieje korelacja między odpowiedziami FFR w zaburzeniach uczenia wynikająca z upośledzenia percepcji dźwięków mowy. Ponieważ FFR jest obiektywną, szybką i skuteczną procedurą, która nie wymaga świadomego udziału pacjenta, wydaje się ważnym narzędziem we wczesnej diagnostyce tych problemów.

Słowa kluczowe: ocena • elektrofizjologia • percepcja słuchowa mowy • zaburzenia uczenia się

Introduction

Electrophysiological assessments are an effective and objective way of monitoring different pathologies. Currently, the frequency following response (FFR) has been described as a biomarker of impaired speech perception in patients with learning disorder. Accordingly, the present systematic literature review aims to show that there is a correlation between the responses of the FFR in learning disorder.

Learning disorder (LD) is a central nervous system disability which involves impairments in skills such as reading, writing, and math. To be diagnosed with this disease, patients must have had difficulties for at least 6 months not attributed to an intellectual disability, lack of visual or auditory acuity, or other mental or neurological issue [1]. The prevalence of LD is around 5–15% of the school population, starting at an early stage of life but in the majority of cases occurring at school age; however, it can persist into adulthood. Severity is based on a variety of test procedures including medical history, clinical interview, school reports, teacher assessments, and psychometric testing [2].

Research has shown a correlation between LD and auditory function performance involving central auditory processes. There is a reduction in temporal processing ability revealed by the random gap detection test (RGDT), gap-in-noise test (GIN), frequency pattern test (FPT), and duration pattern test (DPT), all of which involve difficulty in ordering and temporal resolution skills – that is, in processing the temporal pattern of non-verbal sounds (frequencies, durations, and intervals) and in the melodic contour of words. Temporal resolution plays a fundamental role in the perception and segmentation of speech, in the learning and comprehension of language, and is directly related to phoneme perception and discrimination [3-6].

There are also reports of how LD is associated with changes in certain electrophysiological measures. LD is associated with impaired neural responses that can affect the latency and amplitude of short, medium, and long-latency auditory evoked potentials. Tested subjects with reading and writing disorders who also had changes in long-latency potentials and evaluated whether the subjects also had changes in short-latency potentials [7]. Results showed that, with a normal click stimulus, all 21 subjects presented ABRs. Corroborating these findings, ABRs with click stimuli had no changes; however, changes were evident when verbal (speech) stimuli were used, with the presence of a significant increase in the absolute latency values of waves V and A, as well as the VA slope, suggesting that only those processes involved in coding speech signals in the brainstem are altered in children with learning difficulties [8].

As for findings with the middle latency auditory evoked potential (MLAEP), analyses have shown functional differences in children with LD, with prolonged latency of the Nb component being observed in the left hemisphere [9]. The long latency auditory evoked potential (P300) may be absent, or have increased latency, as well as components P1, N1, P2, and N2 – which are related to attention, memory, and the acoustic and phonetic aspects of acquiring linguistic patterns, all of which are important for learning to read and write [10].

Among electrophysiological measures, the FFR proves to be a valuable tool in the investigation of LD, as it objectively evaluates the representation of how verbal sounds are processed. It also tests the neural response times in the auditory pathway, evaluating the central auditory nervous system as a whole. It is fast, does not require the attention of the patient, and can be used in different age groups and populations [11-12].

The aim of this study was to conduct a systematic literature review from 2009 to 2019 correlating LD with impaired auditory function as seen with the FFR.

Methods

The present study is a systematic literature review, based on international recommendations, and seeks to answer the question "How can the FFR help in the detection or diagnosis of LD?". The bibliographic search used the Scielo, LILACS, Cochrane, and PubMed databases from 2009 to 2019. Filters related to species (humans) and year (2009 to 2019) were used. The descriptors of the DeCS (Health Sciences Descriptors) and MeSH (Medical Subject Headings) terms from the National Library of Medicine were combined using the Boolean operators AND and OR. Thus, the following combinations of keywords were used:

a) "scholastic difficulties" AND "frequency following response"
b) "scholastic difficulties" AND "speech ABR"

Table 1. Description of selected articles

N°	AUTHORS	YEAR	SAMPLE	AGE	INCLUSION CRITERIA	COMPLEMENTARY EVALUATIONS
1	Neef et al. [26]	2017	62 participants (F = 25, M = 37)	11–13 y.o	• No neurological disease • Normal nonverbal IQ • Normal PTA • Normal click BAEP	• K-ABC • Reading, comprehension, and speed of reading • Orthography performance • Phonological awareness • BAKO • Baseline tests for reading and writing skills
2	Lam et al. [27]	2017	87 participants (F = 52, M = 35)	8–13 y.o.	• Normal IQ • Without DD • Normal PTA	• RAN • Processing speed • CTOPP
3	Neef et al. [24]	2016	159 participants (PL = 95, L = 64)	4–7 y.o. (PL) and 11–13 y.o. (L)	• No neurological disease • Normal PTA • Normal click BAEP	• LGVT • DERET • K-ABC • WPPSI-III

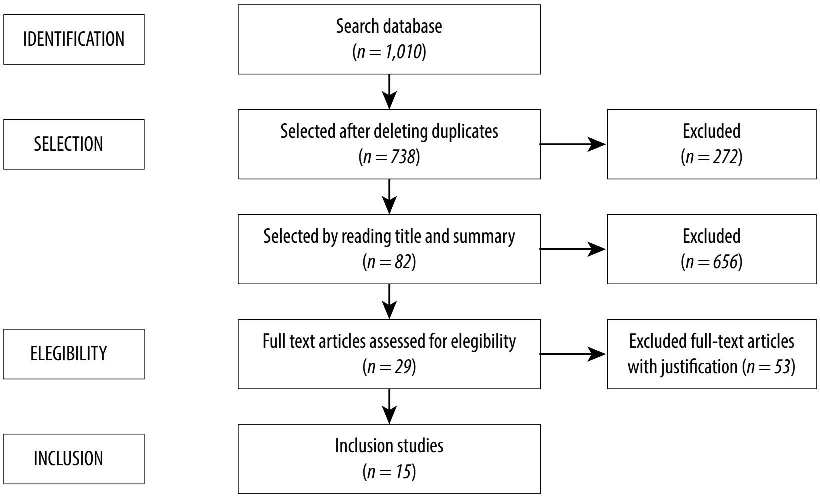

Figure 1. Flowchart of the review

c) "scholastic difficulties" AND "speech auditory brainstem response"
d) "scholastic difficulties" AND "speech perception"
e) "complex sound" AND "learning disabilities" AND "frequency following response"
f) "learning disabilities" AND "speech ABR"
g) "learning disabilities" AND "speech auditory brainstem response"
h) "learning disabilities" AND "complex sound"
i) "learning disorder" AND "frequency following response"
j) "learning disorder" AND "speech ABR"
k) "learning disorder" AND "speech auditory brainstem response"
l) "learning disorder" AND "complex sound"
m) "learning disabilities" AND "complex sound".

Two researchers independently carried out the search according to the inclusion and exclusion criteria. As inclusion criteria, articles that answered the research question and the theme established by the descriptors were selected. Exclusion criteria were national (English language only) and laboratory studies, experiments with animals, opinion/authority articles, case series, and case reports. Data analysis was initially carried out through the titles and abstracts of the articles. Those selected were then subject to a full reading of the text and only those studies that met the established criteria were included. Figure 1 shows a flowchart of the review.

The articles were read, analyzed, and tabulated in terms of the following: authors, year, place, design, sample, age range, tests used, and results (see Table 1).

Results

The sample subjects included children, adolescents, and young people, a total of 1053 individuals aged 3–23 years old. The number of individuals included in each study ranged from 20 to 159. In these studies, the child population was the most evaluated (66.6%, of whom 55.9% were male) possibly because these subjects have greater school demands. Multiple sources found that the incidence of LD was higher in boys than in girls [1,13], although the statistical difference was not so large in this sample.

RESULTS
Children with a reading disorder had both poor phonological awareness and poor physiological discrimination of sounds, measured with the delta cross phase of [da] versus [ba]. The correlation between the quality of literacy skills and the stability of brainstem responses evoked by speech was consistent. Therefore, children with little skill in phonological awareness presented small phase deviations and, therefore, decreased neural discrimination of sounds (i.e. weak subcortical differentiation of consonants), while children with good phonological awareness presented superior neural discrimination.
Poor RAN readers had more variable responses than good RAN readers when examining the variability of the test response (i.e., the FFR of good RAN readers was less variable than poor RAN readers). Children with more stable neural responses to speech showed higher processing speed and better performance of RAN; children with more stable responses were more fluent readers.
Observed unstable representation of sound, and thus reduced neural discrimination capacity of occlusive consonants, occurred in genotypes that had a greater amount of risk alleles KIAA0319. The KIAA0319 gene associated with dyslexia can alter brainstem responses and change the processing of phonemes in the auditory brainstem. Children with a greater number of risk alleles of KIAA0319 had less stable evoked brainstem responses, whereas children with a lower risk burden of KIAA0319 had more stable responses.

N°	AUTHORS	YEAR	SAMPLE	AGE	INCLUSION CRITERIA	COMPLEMENTARY EVALUATIONS
4	White-Schwoch et al. [29]	2015	112 participants (F = 21, M = 16)	3–14 y.o.	• No history of neurological condition • No experience with second language • Normal click BAEP • Normal AS (OT, TYMP, OAE) • Normal PTA	• Child assessment of language basics • CELF-P2 • RAN • PRO-ED • CTOPP 1ª and 2ª • Conquest Test of Woodcock-Johnson-III • Orthography and subtitles of word attack and basic reading compound • TOWRE • WASI • Assembly of objects • Matrix reasoning • WPSSI-III
5	Carr et al. [30]	2014	35 participants (F = 18, M = 17) (S = 22, NS = 13)	3–4 y.o.	• Normal AS (OT, TYMP, OAE) • Normal click BAEP	• WPSSINeurological and Behavioral Vocabulary Test • Clinical Evaluation of Language Fundamentals - preschool • Phonological Awareness • Recollection in a Sentence
6	Malayeri et al. [32]	2014	83 participants (F = 30, M = 53) (TA = 49, NA = 34)	8–12 y.o.	• No history of neurological disease, medical illnesses, affective disorders, or schizophrenia • IQ between 90 and 115 • Diagnosis of LD or ADD • Normal PTA • Normal TYMP • Normal word recognition	• WISC-R
7	Hornickel & Kraus [25]	2013	100 participants (F = 42, M = 58, GR = 34, AR = 34, PR = 32)	6–13 y.o.	• No neurological disease • IQ > 75 • Normal PTA • Normal click BAEP	• TOWRE
8	Hornickel et al. [37]	2013	113 participants (F = 30, M = 83)	6–14 y.o.	• No neurological disease • Scores IQ > 85 • Normal PTA • Normal click BAEP	• TOWRE • Silent Word Reading Fluency Test
9	Kouni et al. [33]	2013	20 participants (DIS = 10, DISM = 10, F = 8, M = 12)C=20	18–23 y.o.	• IQ > 80 • No brain damage, language or visual problems, psychiatric symptoms • Greek as a first language • Normal PTA • Normal WR • Normal SDT • Normal TYMP	• WASI IV
10	Hornickel et al. [35]	2012	38 participants (F = 16, M = 22 FMG = 19, GC = 19)	8-14 y.o.	• IQ > 80 • No neurological disease • For dyslexics, scores below 100 or more than 15 points below the full IQ in the silent reading fluency test or in the vision subtest of the oral reading test • Diagnosis of LD, reading and/or attention • Normal PTA • Normal click BAEP	• WASI • TOWRE • Silent Word Reading Fluency Test • CTOPP subtests • Word Attack and Letter subtests, Classification Scale of ADHD IV

RESULTS
In Expt 1, 37 children (21 F and 16 M) 4 years old presented adequate responses, suggesting that the precision and stability of coding consonants in noise match emerging literacy skills over a wide spectrum of competencies before the start of explicit reading instruction. Using the values applied in Expt 1, 20 children (9 F, 11 M) aged 3–9 years were recruited, where the neural coding of consonants in noise predicted performance in a RAN test and auditory working memory with knowledge of grammar (an additional substrate skill that contributes to the development of literacy and is often deficient in children with dyslexia and/or language impairment). In Expt 3 with 34 children (18 F, 16 M), a subgroup of Expts 1 and 2 who returned after 1 year, it was observed that the neural coding of consonants in noise can predict future reading success in standardized tests, in addition to multiple substrate literacy skills. Then, in Expts 1 to 3, a neurophysiological–auditory biomarker for pre-reading skills in preschoolers was established. The regression model of Expt 1 was applied to perform Expt 4 with 55 children (22 F, 33 M), of which 26 had a diagnosis of LD, where they differed in predicted scores, and the predictions of the models reliably classified the changed diagnostics.The study suggested that the precision and stability of coding consonants in noise matches emerging literacy skills across a broad spectrum of competencies. Neurophysiological markers (time, stability, and the magnitude of responses to consonants) provide a biological indicator to a child's future literacy.
The S group demonstrated a more precise neural coding of speech envelopes than the NS group, evidenced by greater correlations between the brainstem stimulus and response envelopes through stimuli in noise and silence conditions. The ability for individual synchronization within the S group is correlated with more precise envelope encoding (a combination of [ba], [da], and [ga]). The S group showed higher correlations between the brainstem stimulus and response envelopes through stimuli in noise and silence conditions. The individual synchronization capability was correlated with more precise envelope encoding.
The latencies of waves III, V, and Vn and the interpeak latency between V–Vn in the ABR click, and the absolute latencies of waves I, V, and A and V–A interpeak in the sABR were significantly higher in LD children than in NA children.
There was a main effect of the reading group for consistency of the brainstem response to speech in the formant transition, with a tendency effect for the vowel response, but not for neurophysiological noise (pre-stimulus amplitude). Poor readers had brainstem responses more variable to speech than good readers and were marginally worse than average readers in the formant transition portion, in addition to greater variability in the formant transition region than in the vowel portion of the response, an effect that was marginal for average readers and absent for good readers.
In the present study, it was found that the auditory brainstem responses of two siblings of the same sex and learning diagnosis were more similar than responses of pairs of children matched in age and gender, or pairs of children combined with IQ and reading ability. Children who were matched to reading ability had more similar brainstem auditory morphology than children who were matched only with age and sex, reinforcing that specific brainstem auditory characteristics are related to reading ability. The results of the study support that there are different characteristics among poor readers who present characteristic deficits in the representation of the harmonic and temporal elements of speech, compared to their typical reading pairs in the auditory responses of the brainstem to speech.
The absolute peak latencies of the negative C wave and the C–A interpeak latencies elicited by verbal stimuli were shown to be increased in the dyslexic group compared to the control group.
After the children used the FM system for 1 year, their auditory brainstem responses for conversations became more consistent, as evidenced by a greater correlation between the first and the second half of the record. Improvement in the consistency of the neural response was observed for a response to the transition to speech conversations (7–60 ms). The use of the FM system in the classroom produced improvements in the consistency of the neural representation of dynamic components of important conversations to differentiate consonants.

N°	AUTHORS	YEAR	SAMPLE	AGE	INCLUSION CRITERIA	COMPLEMENTARY EVALUATIONS
11	Strait et al. [28]	2011	42 participants (GR = 8, PR = 21, OC = 13)	8-13 y.p.	• IQ > 85 • Normal PTA • Scores ≤90 were included in the poor reading group • Scores ≥110 were included in the good reading group	• Child Behavior Checklist
12	Anderson et al. [31]	2010	66 participants (F = 22, M = 4 4) (LD = 36, ND = 30, LR = 28, UR = 27)	8–14 y.o.	• IQ > 85 • Normal PTA • Normal click BAEP	• HINT • TOWRE-T • WASI
13	Hornickel et al. [36]	2009	43 participants (F = 20, M = 13)	8–13 y.o.	• Normal IQ • Normal PTA • Normal click BAEP	• HINT • CTOPP • TOWRE
14	Chandrasekaran et al. [19]	2009	30 participants (GR = 15, AR = 15)	11–13 y.o.	• IQ > 85 • Normal PTA • Normal click BAEP	• HINT • TOWRE
15	Banai et al. [34]	2009	63 participants (F = 28, M = 35)	7–15 y.o.	• IQ > 80 • Normal PTA • Normal click BAEP	• CTOPP • WRAT-3 • WJ-III

F, female; M, male; PL, pre-literate; L, literate; S, synchronizers; NS, non-synchronizers; LD, learning disorder; NA, normal learning; GR, good readers; AR, average readers; PR, poor readers; DIS, dyslexics; DISM, mild dyslexics; C, controls; FMG, frequency modulated group; GC, control group; OC, other criteria; BR, bad readers; ND, normal development; UR, upper reading; LR, lower reading; IQ, Intelligence Quotient; PTA, pure tone audiometry; BAEP, brainstem auditory evoked potential; DD, developmental disorders; AS, hearing screening; OT, otoscopy; TYMP, tympanometry; OAE, otoacoustic emissions; K-ABC, Non-standard test of reading words and non-words; RAN, rapid automatic naming test; CTOPP, Comprehensive Phonological Processing Test

All articles ruled out hearing impairments, since 100% of the studies performed audiological evaluation with pure tone audiometry and 73% of them performed an evaluation using BAEP-click. In addition, neurological alterations were also removed from the sample by tests that assessed IQ (100%); the most used were the Wechsler Abbreviated Intelligence Scale (26%) and Pre-school and Primary Intelligence Scale, WPPSI-III (20%). According to Snowling and Hulme [14], LD immediately excludes mental deficiency, emotional disturbance, cultural differences, and developmental failures, focusing only on the discrepancy between academic activity and the apparent ability to learn.

As a complementary assessment, 46% of the articles used some test to assess phonological awareness: CTOPP, 33%; BAKO, 6%; CELF, 2–6%; or other unspecified test, 6%. Some 66% of the tests assessed reading: the most used were TOWRE (46%), K-ABC (13%), and Silent Reading Fluency Test (13%). Some 20% of the articles used tests that evaluated orthography (Orthography performance, 13%, and DERET, 6%). The diagnosis of a specific LD is based on persistent difficulties in reading, writing, arithmetic, or mathematical reasoning skills during the formal years of schooling [1]. Symptoms may include inaccurate or slow and laborious reading, unclear writing, difficulty remembering numbers, or inaccurate mathematical reasoning.

In Table 2 one can see that the FFR was carried out with various types of equipment, the most frequent being NeuroScan 4.3 (46%), followed by Biologic Navigator Pro (20%), BrainVision V-Amp (13%), while Intelligent Hearing Systems and ActiABR totaled 7%. One of the articles did not describe the equipment used. Regarding software, about 60% used NeuroScan Stim 2, while 13% used BioMark. About 7% used LabView 2.0 and the other 20% did not describe the software used.

Regarding the diversity of duration of sound stimuli, in the assessment of the coding of verbal sounds it was observed that the majority (93%) used a syllable duration of 170 ms and only one article (7%) used a duration of 40 ms. The authors who used both stimulus durations concluded that both the short (40 ms) and long (170 ms) stimuli well reflected speech coding in the brainstem [15].

Most studies (53%) used the syllable /da/, which is considered a universal syllable, allowing its use in individuals from different nationalities and presents an opportunity to evaluate bilingual children with clear, robust, and reproducible responses [11,12,15]; only one article (7%) used the single syllable /ba/. The studies also demonstrated varied verbal stimuli, such as the combination of the syllables /ba/, /da/, and /ga/ (20%) and bisyllables /ba/ and /ga/ (13%) or /ba/ and /da/ (7%), which are being developed to improve the quality and efficiency of the assessment of the coding of verbal sounds in the FFR procedure [16-17].

Some 73% of the studies used condensation or rarefaction stimulus polarity for collecting responses, while 27% reported the use of alternating polarity. According to Kumar et al., the stimulus polarity does not affect the latency of the various speech peaks of the FFR [18].

Most articles (93%) used monaural stimulation of the right ear, a choice explained by the fact that the right ear has an advantage in speech coding due to the contralateral

RESULTS
The study demonstrated that poor readers have poor subcortical performance of spectral components of speech sounds and that good readers have a greater improvement in speech harmonics than poor readers.
When comparing brainstem responses in groups, children with lower reading and lower SIN had greater delays in the transition period compared to groups. Peak delays corresponded to the formant transition of the evoking syllable, which is the most noticeably vulnerable segment of the speech syllable. Poor perception and reading are associated with decreased neural synchrony, leading to impaired processing of time information in noise.
Children with poor phonological awareness and speech perception in noise had minor or absent latency differences between responses – i.e. the perceptual deficits observed in children with learning difficulties are limited to short, spectrally dynamic elements (formant transitions) and do not affect steady-state vowels. Thus, the subcortical coding deficits observed for children with reading disorders are limited to the temporal (transient) and spectromorphic dynamic elements of the signal and do not include F0.
Children with poor reading ability differed in the extent and nature of the context-dependent spectral coding within the 7–60 ms time period corresponding to the stimulus formant transition, but not during the 60–180 ms time period corresponding to the vowel steady state.
Peak response latencies in good and bad readers were compared for all 7 peak responses. For all peaks, average latencies were lower for good readers than for poor ones. The group differences for peaks V, A, C, D, E, and O and the measure of compound response time were large. In addition to the response of the speech signal harmonics, which were more robustly encoded in good readers than in poor.

K-ABC, Kaufman Assessment Battery for Children; TOWRE, Test Of Word Reading Efficiency; WPSSI-III, Wechsler Preschool & Primary Scale of Intelligence; WASI, Wechsler Abbreviated Scale of Intelligence; CELF-P2, Phonological Awareness and Remembered Phrases; HINT, hearing in noise test; WRAT-3, Wide Range Achievement Test; WJ-III, Woodcock-Johnson; LGVT, Reading Speed Test; PRO-ED, naming time in seconds normalized on a recording scale; WISC, Wechsler Intelligence Scale for Children Revised; LD, learning disorder; ADD, attention deficit disorder; CAE, complete audiological examination; SRT, speech reception threshold; SDT, speech discrimination test; DERET, German spelling test for the first and second school years.

projection of information to the left hemisphere. In addition, it allows a shorter assessment time, with good quality responses, and is recommended for individuals with asymmetric hearing thresholds, children, or populations that are difficult to test [19-21].

In 7% of the articles, the evaluation was performed monaurally in both ears. The studies suggest that binaural hearing provides information about everyday listening environments, such as differences in time and intensity of a sound between ears, in addition to interaural differences in time and interaural level and the location of sound sources [22-23].

The most used fundamental frequency (F0) was at 100 Hz (53%), followed by 250 Hz and 103–125 Hz in 7% of the articles, while 33% did not report these data. The first formant (F1) most used was 400–720 Hz (60%) and 220–720 Hz was also mentioned (7%), while 33% of the articles did not report these data. The second formant (F2) was cited at 1700–1240 Hz (53%), 2580–2500 Hz and 900–1700 Hz in 7%, while 33% of the articles did not report these data. According to Skoe and Kraus [22], speech may contain spectral information above 10 kHz, therefore, the speech stimulus to be used must be carefully selected to ensure that the responses encoded in the brainstem can be captured, and the consonant/vowel distinction generally occurs below 3 kHz.

According to a study by Neef et al., children aged 4–7 years old with a gene associated with dyslexia have less stable brainstem responses, whereas children with a lower risk burden have more stable responses in the FFR 24. Other authors evaluated FFR in twin brothers aged 6 to 14 years diagnosed with LD, where the auditory responses showed an identical electrophysiological marker when compared to twins without diagnosis [25].

In a more recent study, children 11–13 years old with LD had phonological awareness and unstable neural discrimination, whereas children with good phonological awareness showed superior neural discrimination [26]. Corroborating these results, one study showed that children aged 8–13 years old, classified as poor readers, had a more variable response in the FFR, while children considered fluent readers had a more stable response [27]. A similar finding has been described where the most variable response to the sound of speech was in the group of poor readers aged 6 to 13 years [25]. The study divided children aged 8–13 years old into groups of good readers and poor readers; here the FFR demonstrated poor subcortical performance of spectral components of speech sounds in poor readers, while good readers had a greater improvement in the harmonics of speech [28]. This result has been confirmed, finding that children aged 11–13 years old who had poor reading ability differed in the extent and nature of spectral coding [19].

According to Hornickel et al., the response of children with learning disorder are consistent with the view that improper utilization of phonology, probably through a combination of deficits in phonological perception and working memory, is manifested in deficient encoding in the auditory brainstem of sound elements important for phoneme identification [36]. Another study suggested that the ABR could be a particularly useful metric for assessing risk of reading impairment in children who have family members with reading disorders [37].

Table 2. FFR parameters

Article No	Author	Equipment	Software	Stimulated ear	Stimulus	Duration (ms)
1	Neef et al.	BrainVision V-Amp	-----------------	RE	/ba/ /da/	170
2	Lam et al.	NeuroScan Acquire	NeuroScan Stim 2	RE	/ba/ /ga/	170
3	Neef et al.	BrainVision V-Amp	-----------------	RE	/da/	170
4	Branco et al.	Navigator Pro, Bio-Logic Systems	Neuroscan Stim 2	RE and LE	/da/	170
5	Kali et al.	ActiABR	LabView 2.0	RE	/ba/ /da/ /ga/	170
6	Malayeri et al.	Biologic AEP software	Bio-MARK	RE	/da/	40
7	Hornickel et al.	Intelligent Hearing Systems	NeuroScan Stim 2	RE	/ba/ /ga/	170
8	Hornickel et al.	NeuroScan 4.3	Neuroscan Stim 2	RE	/da/	170
9	Kouni et al.	-----------------	-----------------	RE	/ba/	170
10	Jane et al.	NeuroScan 4.3	NeuroScan Stim 2	RE	/ba/ /da/ /ga/	170
11	Dana et al.	NeuroScan 4.3	NeuroScan Stim 2	RE	/da/	170
12	Anderson et al.	NeuroScan 4.3	NeuroScan Stim 2	RE	/da/	170
13	Hornickel et al.	NeuroScan 4.3	NeuroScan Stim 2	RE	/ba/ /da/ /ga/	170
14	Chandrasekaran et al.	NeuroScan 4.3	NeuroScan Stim 2	RE	/da/	170
15	Karen et al.	Bio-logic Navigator Pro	Bio-MARK	RE	/da/	170

Key: dB = decibel; Hz = hertz; SPL = sound pressure level; COND = condensation; RAR = rarefaction; ALT = alternated

The precision and stability of the stabilizing consonants in noise with the neurophysiological markers of time, stability, and the magnitude of the consonant responses, provide a biological pointer to the future literacy of a child when evaluated between 3 and 14 years old [29]. The authors assessed the correlation between the stimulus in silence and noise and the FFR response, and observed that younger children (3–4 years old) diagnosed with LD were considered unsynchronized, demonstrating a less precise neural encoding of the speech envelope, compared to the synchronized children who had a more precise envelope coding (in terms of [ba], [da], and [ga]) [30]. The study showed that older children (8–14 years old) with lower reading ability had a greater delay in the transition period [31].

One study concluded that latency is significantly higher in children aged 8–12 years diagnosed with LD [32]. Another study which evaluated adults aged 18–23 years old found increased latency in a group of dyslexics [33]. A similar study found differences (minor or absent latencies) in children aged 8–13 years old, with lower performance in phonological awareness [11]. Similarly, the study of children aged 7–15 years old found that latency was lower in good readers compared to bad readers [34].

A study in children aged 8–14 years old with LD concluded that the use of an FM system in the classroom produced an improvement in the consistency of the neural representation of dynamic speech components important for distinguishing consonants [35]. The auditory responses of the brainstem to speech became more consistent, as evidenced by a greater correlation between the first and second halves of the record, observed for the response to the formant transition of speech syllables.

Conclusion

The present study, a systematic literature review from 2009 to 2019, concluded that there is a correlation between the responses of the FFR in learning disorder and a loss in perceiving speech.

FFR responses in patients with learning disorder show unstable and more variable neural discrimination, with poor subcortical performance of spectral components, less precise extent and nature of neural coding, delay in the transition period, and significantly longer latency when compared to their healthy peers. In addition, studies have demonstrated that neural discrimination is directly related to phonological awareness and reading performance.

Thus, evaluation of the FFR provides a biological marker for literacy and impaired auditory function in children and adults with learning disorder. Because it is an objective, fast, and effective procedure, which does not require the patient's conscious participation, the FFR can be an important instrument in the early diagnosis of these changes.

Sweeps (No.)	Intensity	Polarity	F0 (Hz)	F1 (Hz)	F2 (Hz)
6200	80db SPL	COND and RAR	100 Hz	400–720 Hz	/ba/ 900 Hz /da/ 1700 Hz
6000	80db SPL	COND and RAR	-----	-----	-----
6000	80db SPL	COND and RAR	100 Hz	400–720 Hz	1700–1240 Hz
Experiments 1–3, 4200; Experiment 4, 6300	80 dB SPL	ALT	100 Hz	400–720 Hz	1700–1240 Hz
6000	80dB SPL	ALT	100 Hz	400–720 Hz	2580–2500 Hz
6000	80dB SPL	ALT	-----	-----	-----
6000	80dB SPL	ALT	-----	-----	-----
6000	80dB SPL	ALT	100 Hz	400–720 Hz	1700–1240 Hz
6000	80dB SPL	ALT	-----	-----	-----
6000	80dB SPL	COND and RAR	-----	-----	-----
6000	80dB SPL	ALT	100 Hz	400–720 Hz	1700–1240 Hz
6000	80dB SPL	ALT	250 Hz	400–720 Hz	1700–1240 Hz
6000	80dB SPL	ALT	100 Hz	400–720 Hz	1700–1240 Hz
6000	80.3dB SPL	ALT	100 Hz	400–720 Hz	1700–1240 Hz
3–2000	80.3dB SPL	ALT	103–125 Hz	220–720 Hz	1700–1240 Hz

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