

CLINICAL SCIENCE

Speech and non-speech processing in children with phonological disorders: an electrophysiological study

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OBJECTIVE: To determine whether neurophysiological auditory brainstem responses to clicks and repeated speech stimuli differ between typically developing children and children with phonological disorders.

INTRODUCTION: Phonological disorders are language impairments resulting from inadequate use of adult phonological language rules and are among the most common speech and language disorders in children (prevalence: 8 - 9%). Our hypothesis is that children with phonological disorders have basic differences in the way that their brains encode acoustic signals at brainstem level when compared to normal counterparts.

METHODS: We recorded click and speech evoked auditory brainstem responses in 18 typically developing children (control group) and in 18 children who were clinically diagnosed with phonological disorders (research group). The age range of the children was from 7-11 years.

RESULTS: The research group exhibited significantly longer latency responses to click stimuli (waves I, III and V) and speech stimuli (waves V and A) when compared to the control group.

DISCUSSION: These results suggest that the abnormal encoding of speech sounds may be a biological marker of phonological disorders. However, these results cannot define the biological origins of phonological problems. We also observed that speech-evoked auditory brainstem responses had a higher specificity/sensitivity for identifying phonological disorders than click-evoked auditory brainstem responses.

CONCLUSIONS: Early stages of the auditory pathway processing of an acoustic stimulus are not similar in typically developing children and those with phonological disorders. These findings suggest that there are brainstem auditory pathway abnormalities in children with phonological disorders.

KEYWORDS: Central auditory physiology; Auditory brainstem response; Speech-evoked auditory brainstem response; Speech encoding; Articulation disorders.

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INTRODUCTION

Auditory evoked potentials are used to assess the auditory pathway in children with language impairments and learning disabilities.^{1,2} The most widely used auditory evoked potentials in clinical practice is the auditory brainstem response (ABR) using click stimuli.^{3,4} Additional methods have been developed to characterize ABRs obtained from the presentation of speech stimuli that

are spectrally and temporally more complex than click stimuli.^{5,6}

The speech-evoked ABR to a consonant-vowel syllable contains an onset similar to the click-evoked response, which is due to the initial noise burst that marks the onset of the consonant, and a frequency following response (FFR) that corresponds to the periodic voiced formant transition.⁷ This perceptual acoustic information is encoded across many levels of the auditory system, including the rostral inferior colliculus, as distinct neural events.⁸

Phonological disorders are the most common speech and language disorders in children, with prevalence of 8 to 9%.^{9,10} The phonological-disabled population is heterogeneous, suggesting that these disorders result from multiple interacting physiological processes reflecting more than one underlying cause.

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Normal auditory physiological processing is essential for oral language development and oral language skills and the presence of an abnormality related to the auditory brainstem responses could represent one of the biological underpinnings of the phonological disorders.

Whereas the acoustic patterns of verbal and nonverbal sounds differ substantially and children with phonological disorders have speech and language impairments, it is important to characterize the auditory brainstem responses evoked by click and speech stimuli in this population. This characterization was not done yet for this specific population, using these two types of stimuli simultaneously. Our hypothesis is that children with phonological disorders have basic differences in the way which their brains encode verbal and nonverbal acoustic signal at the level of brainstem when compared to their normal counterparts.

The aim of the present study was to investigate whether neurophysiological ABR responses to clicks and repeated speech stimuli differed between typically developing children and children with phonological disorders. The specific aims of this study were (1) to compare brainstem responses to clicks and the speech syllable /da/ between children with phonological disorders and typically developing children, and (2) to determine whether there is a relationship between the speech-evoked ABR and the severity of the phonological disorder.

METHODS AND MATERIALS

Study design

This prospective research study was developed at the Auditory Evoked Potentials Lab and Phonology Lab of the Department of Physiotherapy, Communications Sciences and Disorders and Occupational Therapy of the School of Medicine of University of São Paulo (FMUSP). Institutional review board approval for this study was obtained from CAPPesq – HC FMUSP (protocol number 0822/07).

Participants

The subjects were 36 native, Portuguese-speaking children from seven to 11 years of age, who had normal bilateral hearing (pure tone thresholds ≤ 20 dB HL for octaves 250-8000 Hz) and without middle ear problems (normal tympanogram curve and presence of the contralateral acoustic reflex). The control group (CG) was composed of 18 typically developing children (mean age nine years and seven months, 12 boys and six girls). The research group (RG) was composed of 18 children with phonological disorders (mean age nine years and six months, 12 boys and six girls). The children of the research and control groups were matched for age and gender. The parents or legal guardians of the children signed a consent form to approve the children's participation in this study.

The subjects in the RG were referred by the Phonology Lab and were diagnosed with phonological disorders prior to inclusion in this study. These subjects were awaiting speech therapy. The children in the CG were referred by a nursing service of a public health center. The CG children were selected based on the following criteria: no complaints of language and speech disorders, no previous speech therapy, adequate performance in phonology and fluency tests, and adequate performance in reading and writing screening tests.

Stimulus and recording parameters

The children were tested in a sound-treated booth and instructed to ignore the stimuli to minimize the effects of the state of attention or arousal on the recorded responses. ABR recordings were made using silver electrodes (impedance < 5 kOhms), which were placed on the mid-line of the frontal lobe in a 10-20 electrode system (right mastoid reference, forehead ground).

The click stimulus (condensation polarity, duration of 100 μ s) was presented by a PC-based delivery system (GSI Audera). The system controlled the timing and the intensity of stimulus delivery to the right ear through insert earphones (GSI TIP-50) at 80 dBnHL and a stimulus rate of 19.1 clicks/s. Responses were filtered online from 150 to 3,000 Hz and recorded over a 10 ms post-stimulation period. Two thousand repetitions were collected with an amplification of 100,000. Trials with artifacts that measured in excess of ± 25 μ V were rejected from the averaged response. Peaks were selected and their latencies (waves I, III and V) and interpeak latencies (I-III, III-V and I-V) were calculated.

The speech-evoked ABRs were elicited by the formant transition portion of the speech syllable /da/. This syllable was chosen because stop consonants have considerable phonetic information thus providing robust and reliable traces. Stimulus consisted of the first 40 ms of a five-formant speech syllable /da/ and was generated and recorded on a compact disc. The following equipment was used for the procedure: Newman 189 microphone, MACKIE SR32-4 sound table, M-AUDIO 101LT card sound, Sony® Sound Forge 6.0 recording software and Sony® Vegas 4.0 editing software. A native, male Brazilian Portuguese speaker narrated the stimulus. The recording was edited to produce the stimulus according to the parameters described.^{1,11} The stimuli were presented in trains of four stimuli, separated by 12 ms inter-stimulus intervals (ISI: time within a train between stimulus offset and subsequent stimulus onset).¹¹ A JWin All Terrain JX-CD588 discman was used to control the intensity of stimulus delivery. The /da/ stimulus was presented to the right ear through COBY CV 320 supra-aural headphones at 80 dBA and at a stimulus rate of 11.1/s. Responses were recorded by a GSI Audera system over a 50ms post-stimulation time period and filtered online from 100 to 2,000 Hz. Three thousand repetitions (in three different tracings) were collected with an amplification of 100,000. Trials with artifacts that measured in excess of ± 50 μ V were rejected from the averaged response. The final response of each child was a total from 2,000 stimuli (in two reproducible tracings), which were averaged separately and summed to create a mainly neural response representing brainstem activity.¹²

The response to the onset of consonant-vowel syllable includes a positive peak (wave V) followed immediately by a negative trough (wave A).³ Following the onset response, peaks C and F are present in the FFR.³ Whereas other peaks are discernable in this region, peaks C and F were shown to be the most reliable waveform peaks in typically developing children.¹ Peaks were selected, and their latencies and amplitudes (waves V, A, C and F), as well as VA complex parameters (latency, amplitude and slope), were calculated as described.³

Two experienced observers manually marked the wave I, III, and V peaks for the click-evoked ABRs, and the wave V, A, C and F peaks for the speech-evoked ABRs. The identities and the diagnostic categorizations of the children were blinded to the observers.

Table 1 - Control and Research Groups' means and SD of waves I, III, V and I-III, III-V and I-V Interpeaks latency (ms) click-evoked measures.

Click-evoked ABR		Wave I	Wave III	Wave V	I-III interpeak	III-V interpeak	I-V interpeak
Mean (SD)	CG	1.43 (0.09)	3.53 (0.09)	5.41 (0.10)	2.10 (0.13)	1.92 (0.11)	4.02 (0.10)
	RG	1.50 (0.06)	3.64 (0.13)	5.54 (0.20)	2.14 (0.15)	1.91 (0.20)	4.04 (0.18)
p-value		0.01*	0.01*	0.02*	0.43	0.70	0.25

Note: CG – Control Group; RG – Research Group; SD – Standard Deviation. * p-value statistically significant (p<0.05). Normative data¹³: Wave I – 1.54 (0.10); Wave III – 3.70 (0.15); Wave V – 5.60 (0.19); I-III Interpeak – 2.20 (0.16); III-V Interpeak – 1.84 (0.17); I-V Interpeak – 4.04 (0.18)

Mean and standard deviation (SD) were calculated for the click-evoked ABR parameters (peaks and interpeaks latencies) and for the speech-evoked ABR parameters (slope and peaks latencies, and amplitudes) in both the CG and RG and the response measures were compared between groups.

This lab considers parameters for clinical practice, the normative values proposed for the click- and for the speech-evoked ABR.^{13,14}

Speech and language tests

All subjects were tested using standardized Portuguese measures of speech and language performance. The performance on the speech and language tests was assessed using the ABFW Child Language Test.¹⁵ The test is standardized for Brazilian Portuguese and is commonly used for diagnostics in the Phonology Lab. For the CG, the measurements included the phonology and fluency subtests.¹⁵ For the RG, the measurements included the vocabulary, pragmatics, phonology and fluency subtests.¹⁵ The phonology subtest included naming and imitation tasks. Additionally, tests were also used to analyze continuous speech, oral motor skills, and phonological processing. Phonological disorders were characterized by poor performance on the phonology tests with omissions and substitutions of sounds, according to the normative criteria adopted for Brazilian children with no other deviations.¹⁵ The children's phonological deficits were not categorized into subtypes, that is, the children could present both production and reception deficits. Thus, these phonological deviations are reflected as cognitive-linguistic organization impairments. Diagnoses of children with phonological disorders were made by clinical speech language pathologists, independent from participation in the current study.

The collected speech samples were transcribed and analyzed. Then the severities of the phonological disorders were classified. Considering the heterogeneity of the phonological manifestation, we chose to use the Percentage of Consonants Corrects – Revised (PCC-R) index for classification.¹⁶ The PCC-R index is a useful tool for

establishing the baseline of a phonological disorder, establishing diagnoses and monitoring treatment efficacy. Considering the available indices to classify the severity of phonological disorders, the PCC-R is the most appropriate one for comparisons involving speakers of different ages and with different speech characteristics because it only considers substitutions and omissions as errors.¹⁶

Statistical analysis

ANOVA were used for statistical analysis of the latency measurements of the click-evoked ABR. ANCOVA were used for statistical analysis of the latency and amplitude measurements of the speech-evoked ABR. The correlations between the speech-evoked ABR results and the PCC-R index were established using Pearson's correlation. Sensitivity (i.e., how many cases of phonological disorders the test can correctly identify) and specificity (i.e., how accurately it diagnoses phonological disorders without giving false-positive results) were also calculated. The differences between the click and speech sound encoding results in the CG and RG were considered significant when $p \leq 0.05$.

RESULTS

Click-evoked ABR

Statistical analysis performed on the latency values demonstrated that the waves I, III and V latencies were significantly longer in the RG than in the CG (Table 1), although all measures are within the normal range values.

Considering the parameters adopted by this lab, for the click-evoked ABR, the sensitivity for detecting phonological disorders was 0%, and the specificity was 100%.

Speech-evoked ABR

The latency and amplitude values of the speech-evoked ABRs for both the control and research groups are displayed in Tables 2 and 3. Statistical analyses performed indicated that the latencies of both waves V and A were significantly longer in the RG than in the CG. Amplitude responses

Table 2 - Control and Research Groups' latency and amplitude means and SD of speech-evoked measures.

Speech-evoked ABR		Wave V	Wave A	Wave C	Wave F
Mean latency (ms) (SD)	CG	7.41 (0.92)	9.39 (0.97)	19.42 (1.90)	40.10 (1.85)
	RG	8.58 (1.32)	10.32 (1.43)	18.76 (2.55)	40.00 (2.30)
p-value		< 0.001*	0.0003*	0.95	0.58
Mean amplitude (µV) (SD)	CG	0.32 (0.17)	-0.31 (0.17)	-0.34 (0.23)	-0.33 (0.18)
	RG	0.30 (0.15)	-0.35 (0.16)	-0.35 (0.13)	-0.37 (0.13)
p-value		0.51	0.98	0.81	0.73

Note: CG – Control Group; RG – Research Group; SD – Standard Deviation; * p-value statistically significant (p<0.05). Normative Data¹⁴: Latencies – Wave V: 6.54 (1.00); Wave A: 8.00 (1.06); Wave C: 18.12 (2.05); Wave F: 40.27 (1.43). Amplitudes – Wave V: 0.31 (0.18); Wave A: -0.62 (0.23); Wave C: -0.50 (0.22); Wave F: -0.37 (0.26)

Table 3 - Control and Research Groups' means and SD of VA latency (ms), amplitude (µV) and slope (µV/ms) speech-evoked measures.

Speech-evoked ABR VA Complex		Latency	Amplitude	Slope
Mean (SD)	CG	1.97 (0.43)	0.69 (0.14)	0.36 (0.11)
	RG	1.74 (0.67)	0.67 (0.21)	0.43 (0.19)
p-value		0.33	0.64	0.22

Note: CG – Control Group; RG – Research Group; SD – Standard Deviation. Normative data¹⁴: Latency – 1.46 (0.50); Amplitude – 0.93 (0.26); Slope – 0.71 (0.25)

demonstrated that there were no significant differences between the both groups (Table 2) as well as VA complex measures (Table 3).

Considering the parameters adopted by this laboratory in clinical practice, for the speech-evoked ABR, the sensitivity for detecting phonological disorders was 56%, and the specificity was 94.4%.

Speech-evoked ABR versus PCC-R

The relationship between the speech-evoked measures (latency of waves V and A) and the PCC-R index in two different tasks (naming and imitation) was also examined, as shown in Table 4. There was no significant correlation between the wave V and wave A latencies and the PCC-R index in the RG for either the imitation or the naming tasks. Considering that the children of the CG showed PCC-R equivalent to 100% in both tasks (imitation and naming) it was not possible to perform the correlation of this index with the results of speech-evoked ABR for this group.

DISCUSSION

In the present study, ABRs were measured to assess the integrity of neurophysiological responses to both click and speech stimuli in children with phonological disorders.

Click-evoked ABR

Wave I, III and V latencies differed significantly between the both groups (latencies were significantly longer in the RG than in the CG), although the clinical analysis of results indicated that the latency values obtained in both groups were within the normal parameters adopted by this lab in clinical practice.¹³ This suggests that there are subtle differences in brainstem neural timing from the auditory nerve to the inferior colliculus between children with phonological disorders and those who are typically developing. With the exception of waves I and II, each click-evoked ABR

Table 4 - Correlations between the speech-evoked ABR latencies (waves V and A) and the PCC-R index – imitation and nomination tasks for the research group.

Pearsons Correlation	Wave V		Wave A	
	I	N	I	N
PCC-R				
R	0.063	0.02	0.14	0.03
p- value	0.81	0.91	0.56	0.88

Note: I – Imitation test; N – Naming test; PCC-R – Percentage of Consonants Corrects - Revised

component presumably has multiple generators and conversely, the same anatomic structure can contribute to the generation of more than one peak.⁴ According to Musiek,¹⁷ these structures are organized to encode rapid timing changes in auditory signals with extreme accuracy. Thus, differences in neural representation on the order of tenths of a millisecond are clinically significant.

There are controversies in the literature regarding the click-evoked ABR differences encountered between typically developing children and impaired populations (auditory processing disorders and language impairments). Some studies have suggested that the ABR latencies, resulting from the processing of simple stimuli, such as clicks, are similar in typically developing children and those diagnosed with learning disabilities and/or speech and language impairments.^{1,18} On the other hand, some authors reported differences in wave latencies when comparing typically developing children with those with language disorders for: wave I;¹⁹ absolute and interpeak ABR latencies;²⁰ subtle differences in click-evoked ABR latencies.²¹

Similarly what was observed by those authors, our results revealed that children with phonological disorders presented a subtle delay on the click-evoked ABRs when compared to those typically developing. However, even if differences between groups were found, the effects of desynchronization were less evident, although the clinical analysis (parameters adopted by this laboratory in clinical practice¹³) showed latency values within the normal limits in both groups. These findings indicate the click-evoked ABRs were not sufficient to identify possible abnormalities in this portion of the auditory pathway in children with phonological disorders.

Speech-evoked ABR

The children with phonological disorders demonstrated a poorer representation of speech. There was a significant difference between the groups in terms of the wave V and A latencies, with longer latencies in the RG. Longer latencies in speech-evoked ABRs also have been observed in learning-disabled subjects.^{1,2,22}

Our results suggest the presence of abnormalities in the generation of waves V and A in the speech-evoked ABRs of children in the RG. Waves V and A are thought to be largely generated by the lateral lemniscus and/or inferior colliculus.^{2,11} A direct correlation between the structures of the brainstem and ABR waves cannot be made whereas these complex far-field responses most certainly reflect overlapping activities from multiple neural regions. Consequently, deficiencies in these local processes, mainly during critical developmental periods, could lead to changes in subcortical structures that then affect sensorineural coding of speech stimuli.²³

Furthermore, authors¹¹ suggested that the presence of abnormalities in lower levels of the auditory pathway might limit the effectiveness of processing acoustic information at the cortical level. Similarly, correlations between the temporal aspects of brainstem-evoked responses and cortical asymmetry for the processing of speech sounds were reported.²⁴ These results reinforce the idea that the timing deficits reflected by the brainstem in electrophysiological measurements could affect the cortical processing of acoustic information.

There were no significant differences between the groups with respect to the C and F latencies, the V, A, C and F amplitudes, or the VA parameters. In contrast with our results, delays in the FFR of children with learning problems were reported¹ and authors^{2,11} observed abnormal response magnitudes and slope values in a group of language-impaired children. Our results that indicated only onset response differences between groups support the hypothesis which proposed a dissociation between the onset response and FFR.²⁵ According to the authors, these responses represent different building blocks of the message, which have different encoding demands.

One possible explanation of our findings is that the group differences result from temporal processing differences that could reflect desynchronized auditory firing in the RG.²⁶ The acoustic structure of speech is characterized by rapidly changing spectral patterns.¹¹ Thus, the reduced capability to process, understand and distinguish complex sounds could affect certain skills necessary for the normal development of language.

Relation between Speech-evoked ABR latencies and PCC-R index

The analyses of the relationship between phonological disorder severity and the speech-evoked ABR results led us to conclude that phonological profiles of children with phonological disorders with either normal or abnormal speech-evoked ABRs are similar. Children with delayed onset responses to the speech stimulus did not present lower PCC-Rs when compared to children who did not show delayed onset responses. Similarly, authors found no differences with regard to the reading and writing skills among children with learning disorders with normal and abnormal speech-evoked ABR results.²⁷ Both of these results support the idea that the speech and language disorders, as well as learning disabilities, arise from the interaction of multiple physiological processes.²⁸

Differences of click- and speech-evoked ABRs and relevance of neurophysiological indices to phonological disorders

Studies have suggested that click and speech stimuli recruit distinct neuronal populations²⁹ and have different maturational patterns.⁸ In this study, differences in ABR responses are present in both click and speech stimuli, which demonstrate that the abnormal processing is not stimulus-specific. Nevertheless, more pronounced differences between control and research groups were found in speech-evoked ABR than in click-evoked ABR. Taking into account the mean age of the participants, the matching of the participants by age and gender between RG and CG, and the fact that the responses already have reached the adult patterns for this age group (maturation for click evoked ABR until two years of age²⁹; maturation for speech-evoked ABR until approximately five years of age⁸), our results support the hypothesis that whereas there may be some shared processing reflected in the click and speech onset latency measures, there is also a separate component unique to the processing of complex auditory signals, such as speech.^{21,25}

Indeed, authors²¹ described that both click and speech stimuli evoke different responses, based on the acoustic characteristics of the evoking stimuli. Furthermore, these authors hypothesized that the speech stimulus may be more

challenging to the auditory system because the periodic portion of the vowel may mask the abrupt onset of the consonant. Additionally, differences between the encoding of the click and the speech stimuli suggests that abnormal speech-evoked ABRs may be based on differences in synchronization of the response generators. Thus, if the brainstem is more sensitive to desynchronization effects, the impact will become apparent in response to the speech stimulus, which is longer in duration and has a more gradual onset than the click stimulus.^{11,21}

In addition, our findings demonstrate that the onset synchrony of auditory brainstem neurons differs between normal children and some children with phonological disorders, suggesting that these children present differences specifically in response timing. Some studies suggested that abnormal speech encoding at low levels, such as the brainstem, may have broad consequences on neural encoding throughout the entire auditory pathway.^{24,30} By contrast, this abnormal encoding throughout the entire auditory pathway could reflect a deficit related to corticofugal modulation that affects cortical and subcortical structures.⁸

Our results regarding the sensitivity and specificity of click- and speech-evoked ABR reinforce the idea proposed by authors²¹ once the speech-evoked ABR showed higher sensitivity and specificity than the click-evoked ABR for detecting phonological disorders. Therefore, we suggest that the speech-evoked ABR is a useful tool in the evaluation and monitoring of language disorders in clinical practice.

In summary, our results suggest that abnormal encoding of speech sounds may be a biological marker of phonological disorders. However, these results do not lend themselves to define the biological bases of phonological problems.

CONCLUSIONS

We have demonstrated that at early stages of the auditory pathway processing of an acoustic stimulus are not similar in typically developing children and those with phonological disorders. Considering that, the importance of measurements of the brainstem response in children with language impairments should be emphasized. Also, future researches are needed to investigate the cortical responses in this population and its relations to the auditory brainstem responses.

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