An Alternative Way to Analyze and Predict Consonant Clusters Productions in Brazilian Portuguese Phonological Assessments

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Abstract: To conduct phonological assessments in children, it is necessary to have a set of words that contains a representative sample of adult vocabulary. One of the obstacles to obtain a minimal set is the need to include words with various consonant clusters so that such complex phonetic structures can be validated. In the current literature, there is only one way to determine whether a child is capable of producing a consonant cluster: through the application of a phonological assessment, which contains several words with diverse phonetic structures to be evaluated. In this context, logical inferences are one of the fundamental pillars in any learning area, as they establish logical connections between information to form knowledge about a specific subject. This work proposes an alternative way to indirectly assess a child's ability to produce consonant clusters, based on their ability to articulate similar clusters. The proposed algorithm is fed with the consonant clusters produced and not produced by the child during the assessment. The goal is to discern which other clusters the child is capable or incapable of producing, using the separation of consonant clusters into simpler phonetic structures. The method was validated with a database containing over 1200 phonological assessments conducted in school-age children, native speakers of Brazilian Portuguese. The accuracy of our approach was 97% with 12% false positives and 8% false negatives, indicating that the method is interesting and significantly faithful to real-world results but still leaves room for future improvements. Nevertheless, it is believed that it can be used to reduce the number of words needed in a phonological assessment, through indirect evaluation of specific phonetic structures.

1 INTRODUCTION

In the context of speech therapy, phonological assessments are conducted in school-age children to identify the phonemes they can produce satisfactorily and to detect possible phonological disorders (Usha and Alex, 2023). However, this task demands time from both the therapist and the child, often extending to approximately 1 to 1.5 hours (Combiths et al., 2022), and the process is influenced by the number of target words included in the assessment. In the southern region of Brazil, where this work was conducted, Brazilian Portuguese is used as the native language, and there are different phonological assessment tools in the country containing different sets of words (Yavas et al., 2001; Savoldi et al., 2013; Ceron et al., 2020). Each of these tools is adapted to the regional context and incorporates words representing familiar figures in children's vocabulary (Sotero and Pagliarin, 2018).

Despite advances in the field, traditional methods of phonological assessment still rely on pen-and-paper approaches, lacking software-based solutions (Hódi and Tóth, 2023). Such solutions are compatible with speech therapy due to their audiovisual nature (Uberti et al., 2022) and represent cost-effective alternatives to traditional methods (Usha and Alex, 2023). Internationally, there is a growing effort to develop computational solutions aimed at making this area of pediatric speech therapy more efficient and accessible to society (Räsänen et al., 2021; Strömbergsson

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et al., 2022). However, it is noteworthy that these solutions are often applied mainly for research purposes and lack effective commercial implementation (Uberti et al., 2020).

In the field of speech therapy, determining an individual's ability to produce a phoneme requires that the phoneme to be articulated correctly on at least two occasions (Stoel-gammon, 1985). This requirement implies the need for equivalent words in phonological assessment, i.e., words that possess the same phonemes in the same positions. However, this approach contributes to an increased number of words in the assessment (Marques. et al., 2023), resulting in a potential redundancy in the evaluation of phonemes.

Thus, consonant clusters also represent a significant challenge in the quest for a reduced set of words, as assessing each consonant cluster demands the identification of two other words with the same occurrence. Additionally, it is important to note that consonant clusters are complex linguistic structures, making the task of finding words that not only share these structures but also represent familiar elements in children's vocabulary non-trivial. This aspect adds an additional layer of complexity to the lexical selection process, highlighting the need for more refined strategies in phonological assessments.

Therefore, this study aimed to computationally analyze the set of 84 words proposed by (Ceron et al., 2020) as the basis for a pediatric phonological assessment tool. Our proposal introduces a computational logic capable of inferring whether a child can produce a consonant cluster "XY" through words that contain at least a part of it, i.e., words with other similar consonant clusters like "XW", "ZY", "QX" etc. This idea is based on the hypothesis that if a child can produce at least parts of consonant clusters, they can produce the consonant clusters formed by those parts. Additionally, we applied the reverse logic to identify the structures that the child would not be able to produce.

To validate our proposal, we used a database containing over 1200 phonological assessments conducted on 1357 school-age children (3–7 years old) in the southern region of Brazil. Each assessment used the set of 84 words from (Ceron et al., 2020), and all words were verbalized by the children and transcribed in the database by the speech therapist.

Our results indicate that analyzing consonant clusters separately reduces the minimum number of words needed to validate the phonemes the child can articulate. Furthermore, the reduction of words does not impact the indication of phonological disorder observed in the assessment, meaning the same conclusions can be reached using fewer words.

Finally, our inference logic was validated, and we observed that 97% of the inferred consonant clusters that the child would be able to produce were indeed produced by the child. Conversely, we obtained 12% false positives, indicating that the child would be able to produce more phonemes than they actually did. Additionally, the negative predictive value was 74%, suggesting that the reverse logic to identify consonant clusters the child would not be able to produce still has room for improvement in future work.

The structure of the paper is as follows. In Section 2, we present the main concepts related to this work. In Section 3, we detail our proposal, and in Section 4, we present how the proposal was validated. Finally, in Section 5, we conclude the paper with our final considerations.

2 BACKGROUND AND CONTEXT

The study conducted by (Marques. et al., 2023) revealed a notable overrepresentation of certain phonemes in specific positions within the set proposed by (Ceron et al., 2020). This implies that using this set in a phonological assessment tool may result in generating redundant data. In this scenario, the speech therapist, when guiding the patient in producing a word, may at times be requesting the articulation of phonemes that have already been previously validated at least twice, a redundancy that could compromise the efficiency of the evaluation process (Marques. et al., 2023).

Through exploratory research, we found that there is a collaborative effort between the fields of speech therapy and information systems to develop tools that assist in the identification and diagnosis of phonological disorders (Jothi and Mamatha, 2020; Attwell et al., 2022). The interest in telemedicine solutions in speech therapy has also increased, especially after the global outbreak of COVID-19 (Uberti et al., 2022; Bahar et al., 2022; Patel et al., 2022; Gallant et al., 2023). The use of computational tools in this field is also attractive as they represent cost-effective solutions compared to traditional methods of identifying speech deficiencies and subsequent therapeutic monitoring (Usha and Alex, 2023). However, the large number of words in a comprehensive phonological assessment complicates the screening process for cases that truly require special attention.

Focusing on reducing the 84 words in the set proposed by (Ceron et al., 2020), our work aims to predict the child's ability to produce consonant clusters based on their successes and errors. We introduce a simplified method to verify which of these clusters the child can or cannot produce, breaking down these complex phonetic structures into simpler units. Then, by permuting these units to reconstruct complex structures, we identify other consonant clusters not yet assessed, suggesting the child's ability to reproduce them. Thus, it was possible to observe that in 97% of cases, if the child could produce the hypothetical consonant clusters "XY" and "ZW", they could also reproduce the similar clusters "XW" and "ZY".

This approach represents a perspective on evaluating phonetic structures indirectly, substantially reducing the need for a large number of words in a phonological assessment. As advances in telepractice in speech therapy continue to emerge (Chronopoulos et al., 2021), similar approaches can even be used to replace traditional methods of phoneme assessment, since logical and statistical conclusions can be drawn from the analysis of a limited set of data without compromising the quality of results.

2.1 Speech Therapy Concepts

In speech therapy, phonemes are analyzed in different positions within the syllable and word (Armostis et al., 2022). According to (Stoel-gammon, 1985), in order to validate that a child is capable of articulating a specific phoneme, it is necessary to assess them at least twice. In the context of Brazilian Portuguese, phonemes are evaluated in each of the following positions.

- (OI) Initial Onset: beginning of syllable, word beginning - **c**a.sa [*house*];
- (OM) Medial Onset: beginning of syllable, middle of the word - ca.**v**a.lo [*horse*];
- (CM) Medial Coda: end of syllable, middle of the word - ca.da**r**.ço [*shoelace*];
- (CF) Final Coda: end of syllable, end of the word - a.mo**r** [*love*];
- (OCI) Initial Complex Onset: beginning of syllable, beginning of word - **Br**a.sil [*Brasil*];
- (OCM) Medial Complex Onset: beginning of syllable, middle of the word - bi.**bl**io.te.ca [*library*].

In this work, we are particularly interested in the positions *OCI* and *OCM* as they indicate the presence of consonant clusters. In Figure 1, it is emphasized that the productions of the phonemes "br(OCI)" and "br(OCM)" need to be differentiated, despite being productions of the same cluster "br". This is because a child may find it easy to produce the cluster at the beginning of words but may have difficulty of producing it in the middle of words. Such differentiation helps the speech therapist better identify the phonological articulation skills of children and possible related deviations. To validate the assessment, we need two more words that stimulate the production of these same consonant clusters, or in the best-case scenario, a word that simultaneously contains the same cluster in both OCI and OCM. Thus, there is a tendency for a significant increase in the number of words in an assessment, stemming from the need to directly evaluate consonant clusters.

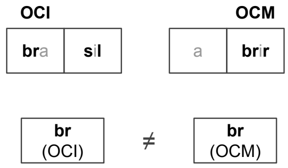

Figure 1: Productions of the same consonant cluster in different positions are considered as different productions.

Thus, if we were able to apply a logic to infer an individual's ability to articulate a consonant cluster in a specific position without the need for a direct assessment, it would be possible to reduce the set of words in the evaluation. This would lead to the exclusion of words whose sole purpose is to encourage the production of clusters that have already been indirectly evaluated. Consequently, it would increase the efficiency of the assessment by using fewer resources to reach the same conclusions. This is the focal point of our study.

3 INFERRING CONSONANT CLUSTERS PRODUCTIONS BY SPLITTING

After analyzing the set from (Ceron et al., 2020) and identifying all target phonemes, it was found that there are 16 consonant clusters in the set. To analyze all of them at the word-initial position (OCI) and word-medial position (OCM), we would need 2 occurrences for each phoneme, totaling 32 occurrences. However, only 19 of these possibilities are evaluated in the studied set, and of those, 14 are evaluated at least 2 times, as shown in Figure 2. This indicates that there would still be a shortage of words to adequately evaluate all the consonant clusters in the set.

This work observed that the search for another word with the same consonant cluster becomes easier when separating them into smaller phonetic structures, as shown in Figure 3. So, we start to break the consonant clusters into smaller parts, instead of analyzing them as they appear on the words, and we observed that a inference logic could be applied.

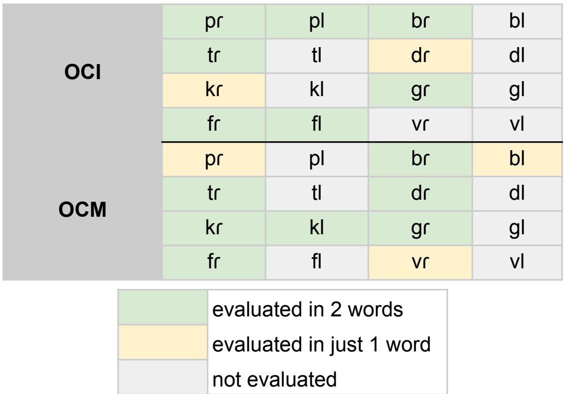

Figure 2: All consonant clusters found in the set proposed by (Ceron et al., 2020).

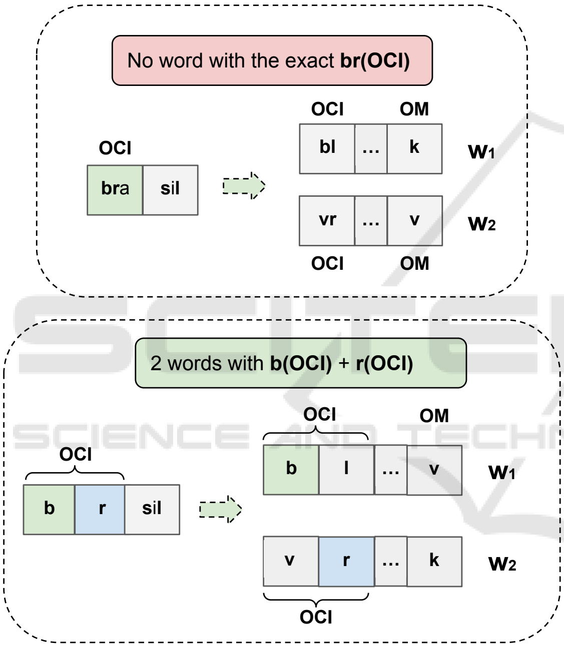

Figure 3: Searching for words with the exact consonant cluster *vs* searching for words with parts of the consonant cluster.

3.1 Inferring Phonemes Capable of Reproduce

Our approach introduces an inference logic capable of predicting the consonant clusters that a child would be able to produce based on the clusters that the child has already produced at least once. This approach analyzes each phoneme individually that constitutes the consonant cluster, based on the premise that if the child was able to articulate the clusters XY and ZW in a specific position, then they are also capable of producing XW and ZY in the same position. If this logic holds true, it would be possible to test by inference the other clusters highlighted in gray in Figure 2 without the need to include more words in the assessment solely for these clusters. Moreover, it would be possible to remove words from the assessment that serve only to evaluate a consonant cluster that has already been inferred that the child is capable of producing, making the assessment shorter as it takes place.

We implemented a simple verification method presented in Figure 4. It is important to note that we validated only the inferences of the colored phonemes presented in Figure 2, which are present in the target words. This is because it would not be possible to validate inferences of phonemes that the child was not stimulated to produce, as we would not have the necessary basis for validation.

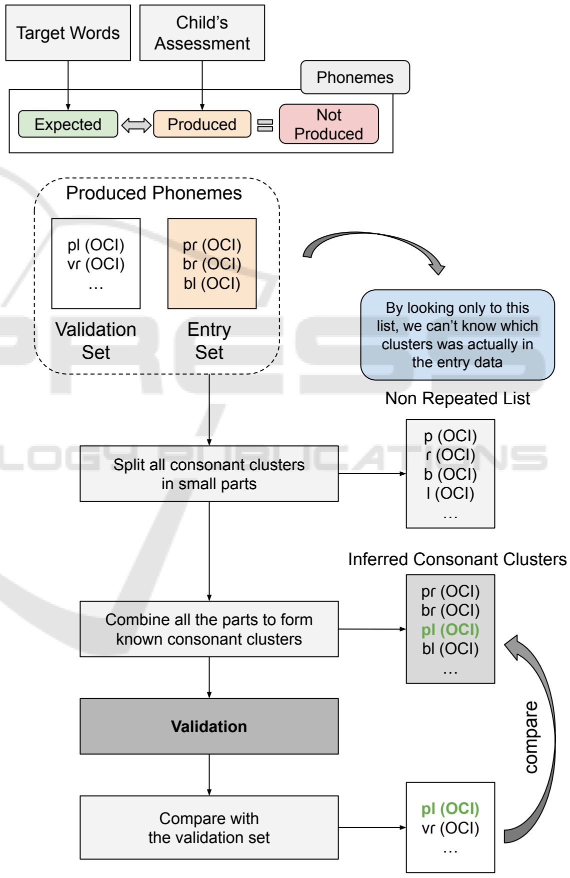

Figure 4: Algorithm to infer consonant clusters that the child is able to reproduce.

3.2 Inferring Phonemes not Capable of Reproduce

In addition, we employ reverse logic to infer the consonant clusters that the child would not be able to produce. This approach is based on the consonant clusters that the child was unable to produce in the assessment, using the same strategy shown in Figure 4.

From here, we have the following analysis: for each word in the assessment, we check which consonant clusters were expected to be produced by the child and what was actually produced; then, we add to a list the parts of the consonant clusters that were *not reproduced*. For example, if it was expected in a word that the child would reproduce the cluster “br” but they produced “bl”, making a substitution, then only the “r” should be added to the list of non-reproduced parts.

4 VALIDATION AND RESULTS

We introduced a method that involves analyzing consonant clusters in smaller parts, allowing the inference of which clusters the child would or would not be able to produce based on these parts.

To validate whether our approach is consistent with real-world results, we executed the method on our database to verify if the observed results align with real-world data. In total, 1294 phonological assessments were analyzed, conducted with 1357 children aged 3-7 years. In each assessment, children reproduced the 84 words from the set of (Ceron et al., 2020), and their transcriptions were stored in our database by a speech therapy specialist. Finally, each transcription was analyzed using the method shown in Figure 4.

It was observed that 76% of the inferences made are of clusters that the child would be able to produce, while only 24% are from the reverse logic. This is explained by the fact that our database consists of 82% correct transcriptions, which represents an imbalance regarding incorrect cases. Consequently, this reflects in the quantity of inferences of consonant clusters that the child would not be able to produce, as such inferences are primarily based on cases containing phonemes that the child was unable to produce, which are present mostly in incorrect transcriptions. The complete result is shown in Figure 5.

		Real Classification	
		True	False
Total Population	24974	19994	4980
Predicted Classification	True	19511	581
	False	1586	4605

Accuracy	0,97
Negative Predictive Value	0,74
Sensibility	0,98
False Positive Rate	0,12
False Negative Rate	0,08
Specificity	0,92

Figure 5: Confusion Matrix of our logic of inference.

OCI	pr	pl	br	bl
	tr	tl	dr	dl
	kr	kl	gr	gl
	fr	fl	vr	vl
OCM	pr	pl	br	bl
	tr	tl	dr	dl
	kr	kl	gr	gl
	fr	fl	vr	vl

- evaluated in 2 words
- evaluated in just 1 word
- not evaluated directly (but inferred)

Figure 6: All possible consonant clusters in Brazilian Portuguese with inferred phonemes by our method.

As shown in Figure 6, our method was able to cover all possibilities to evaluate consonant clusters in the phonological assessment of (Ceron et al., 2020). This indicates that, by employing an inference method like ours, we can indirectly evaluate other phonemes without the need to expose the child to additional words in the assessment, providing greater efficiency to the process.

Currently, our research group is working on a digital platform for phonological assessments, which should include functionalities such as obtaining the child’s phonetic inventory – a list of all the phonemes they are able to articulate satisfactorily. Additionally, the platform will also have a contrastive analysis module, which aims to identify the contrasts between the child’s speech and that of an adult, providing a report on which phonemes the child struggles with the most.

We developed the method proposed in this study with the assistance of speech therapy specialists from our group, and we already received a partial positive validation from them. However, this method will need to be validated in-depth when the platform is released to our research colleagues, who will test it and provide their feedback. This way, our method can be validated in field and we can launch it to the general public in the next months, after adjustments to the platform containing the proposed method as part of the system.

4.1 Analysis in Real Context

Finally, this subsection will present how the logic introduced by this work can be applied in the real world in phonological assessments.

In the algorithm proposed by (Marques. et al., 2023), words were processed as they appeared in the set, without any specific criteria. The present study analyzed how many words would be necessary in the set of (Ceron et al., 2020) to evaluate the same phonemes in the same positions by varying two criteria:

- The order of evaluation of the words;
- Whether or not to separate consonant clusters.

Regarding the order of evaluation of the words, the analysis occurred in two ways: first, analyzing the easiest words to the most difficult, and then in reverse order. The degree of difficulty of the words was directly related to the number of errors recorded for each word in our database. In short, words with more errors would be the most difficult words. Finally, we applied a flag that would determine whether consonant clusters would be evaluated separately or not to determine the impact of the logic introduced by our study.

It was observed that, when not separating consonant clusters, the number of words needed to validate the child's phonetic inventory was higher, as shown in the graph in Figure 7. This is because it is more difficult to find an exact consonant cluster separately than the combination of simple phonemes that form the cluster. Thus, we can replace a direct production with an inference, eliminating the need to evaluate consonant clusters entirely, only their parts.

Finally, as the number of words was reduced, we also assessed the impact of this reduction on the indication of speech disorder, obtained through the *PCC-R (Percent of Consonants Correct-Revised)* by (Shriberg et al., 1997) shown in Equation 1. This index is widely used in the field of child speech therapy as an indication of the level of phonological disorder present in the child's speech (McCabe et al., 2023; Ceron et al., 2017), as shown in Table 1. The value is calculated based on the number of correct productions of phonemes (PC) divided by the total number of productions (TP), and them can be multiplied by 100 to have the percentage.

$$\text{PCC-R} = \frac{PC}{TP} \times 100 \qquad (1)$$

Table 1: Indication of speech disorder according with PCC-R value (Shriberg et al., 1997).

PCC-R Value	Indication of Disorder
Less than 50%	High
Between 50% e 65%	Moderate-High
Between 65% e 85%	Low-Moderate
Greater than 85%	Low

We measured the PCC-R for each of the assessments observed in this study using all 84 words, and associated an indication of speech disorder according to Table 1. This indicator was taken as the validation base, since it uses all words of the original set. The next step was to perform the same measurements, but now using subsets of words obtained in each scenario addressed earlier.

The result is shown in Figure 7. It was observed that, by using the logic introduced by this study and separating consonant clusters to reduce the number of words in the assessment, there were no significant changes in the accuracy of the indication of phonological disorder compared to the original set. Furthermore, by not separating consonant clusters, the number of words needed in the subset slightly increases without changing the accuracy, indicating an unnecessary amount in words.

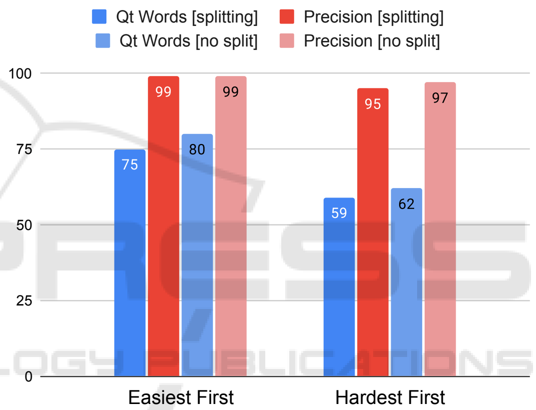

Figure 7: Number of words needed in the set and the relationship with the accuracy in predicting the indication of phonological disorder.

5 CONCLUSIONS

In this study, we introduced a method to infer a child's ability to produce consonant clusters based on their ability to articulate similar clusters. In the literature, computational methods have been applied in the field of pediatric speech therapy. An example of this is the paper of (Franciscatto et al., 2019), where existing phonological processes in a child's speech were predicted through audio analysis and the application of machine learning. However, while this study is being writing, no evidence has been found linking the ability to articulate consonant clusters with the ability to articulate similar clusters.

We employed a logic based on breaking down these complex phonetic structures into elementary structures. Our logic is grounded in the premise that:

"if a child can produce the consonant clusters XY and ZW in a specific position, then they can also produce XW and ZY in the same position". The phonological assessment model studied in this work consists of 84 words, a considerably high number for a 3–7 years old child to verbalize in a speech therapy session. With our method, we could eliminate words from phonological assessments by inferring consonant clusters that the child can produce indirectly.

To validate our approach, we analyzed 1294 phonological assessments conducted in Southern Brazil. Each assessment contained the 84 words proposed by (Ceron et al., 2020), which were verbalized by the children and transcribed in our database by experts in the field. In each assessment, we obtained a list of consonant clusters that the child produced and that were present in the target words, which are the clusters expected to be produced by the child during the assessment. The list of clusters that the child did not produce was also collected.

Finally, we reanalyzed each assessment with our method, going through all transcriptions and breaking down the consonant clusters that the child produced and did not produce into smaller phonetic parts. At the end of the analysis, our method was able to predict with 97% accuracy the articulation ability of the inferred consonant clusters. However, our approach had a false positive rate of 12% and a false negative rate of 8%, indicating that the method predicts more than ideal and still has room for improvements.

As future work, we will include adaptations to the method to predict consonant clusters that the child would not be able to produce, as the negative predictive value was 74%, a value slightly low compared with the general accuracy of the method. Additionally, we believe that there is potential to apply the same logic to predict other types of phonemes in the language, based on their similarity and position in words.

In conclusion, our approach introduces a fast way to infer the child's capability of producing consonant clusters, eliminating the need for more words in the phonological assessment tool. By proposing a new set of target words for an assessment, our method can be used to discard the need to directly evaluate certain consonant clusters in the language. This also reduces the assessment time and subsequent report filling by the speech therapist, as fewer words would be needed in the analysis. Thus, the assessment used by speech therapists would become more efficient, achieving equally reliable results with less effort.

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