

Analyzing clinical phonological data using Phon

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Abstract

In this paper, we describe how Phon, a software program for the transcription and analysis of phonological data, can be applied to facilitate clinical phonological analyses. We begin with a summary of the types of analyses that are frequently used in the assessment and management of speech sound disorders. We then discuss challenges inherent to the transcription and analysis of clinical phonological data. For each challenge, we discuss solutions currently available within Phon, and offer an outlook on future methodological and technical developments in the area of clinical phonology. This paper includes a step-by-step introduction to Phon suitable for readers who lack previous experience with the software. We conclude with a discussion of data sharing and its vital role in advancing research and intervention practices in the area of speech development and disorders.

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INTRODUCTION

Phon is free and open-source software that has been developed over the past ten years as part of the PhonBank project. PhonBank, an offshoot of the longstanding CHILDES¹ project, aims to advance the study of child speech development by aggregating phonological corpus data and maintaining these resources in a searchable database. Phon has evolved over time to support every step of the process of building and analyzing phonological corpora; it now features an array of functions specifically designed to facilitate the study of child phonology.^{2,3} While the development of Phon has historically been guided by the needs of students and researchers in phonological development, in the past two years the Phon team has shifted its focus to the clinical analysis of phonology. With input from a number of active clinical researchers, Phon's powerful analytical tools have been refined and repurposed to be more directly applicable to the assessment and management of speech sound disorders. (Note that while "child" speech is used as an example throughout, Phon can be used with all types of child and adult phonological data.)

A speech-language pathologist analyzing a client's phonology faces many of the same complex demands encountered by researchers in phonological development and disorders. For example, both researchers and clinicians need to identify patterns of substitution, deletion, or insertion and examine the rate of occurrence of these patterns across different contexts.^{4,5} At the same time, we recognize that the clinician faces additional demands in connection with heavy caseloads, documentation requirements, and an increasingly multilingual client base. Technology has often been held out as a solution to these challenges,⁶ but historically, uptake of computerized tools for phonological assessment and analysis has been low.⁷ We show that Phon, whose development has been supported for over a decade in the context of a federally-funded research endeavor, has the potential to represent a more sustainable solution. Bringing the clinical and research communities together around a shared toolkit can benefit both groups by bringing clinical insights into research while simultaneously increasing uptake of evidence-based practices.

We begin with an overview of the PhonBank project and a description of the functions of Phon at the broadest level, followed by a brief review of the most typical components of the clinical assessment and analysis of phonology. Assuming no previous background with the software, we describe in detail how Phon can be used to streamline the process of transcribing, annotating, and analyzing child speech data, and progress to tools developed specifically for clinical applications. Finally, we discuss a number of potential extensions that can increase the clinical utility of future versions of Phon, as well as opportunities for data sharing that can benefit clinicians and researchers alike.

PHONBANK AND PHON

The PhonBank Project, which began in earnest in 2006, is an extension of the Child Language Data Exchange System (CHILDES)¹ into the realm of phonetics and phonology. Since the early 1980s, CHILDES has provided specialists in language acquisition with a wealth of resources to facilitate the study and sharing of child language data. However, CHILDES corpora are, for the most part, transcribed orthographically; technical limitations, such as incompatibilities between different sets of phonetic characters, hindered the development of a standard level of phonological coding. While many proposals to address these issues have been put forward since the 1990s, none of them combined all the features needed for a fully functional solution (see Rose and colleagues^{3,8} for an overview of early systems). To fill this important area of need, Brian

MacWhinney (Carnegie Mellon University) and Yvan Rose (Memorial University of Newfoundland) obtained funding from the National Institute of Child Health and Human Development to launch PhonBank as a large-scale shared database system for the study of phonological development. A cornerstone of this project is the development of Phon, a software program custom-designed to overcome the technological challenges of phonological data entry and analysis. After years of development by professional programmers, Phon is now a powerful program to store and analyze child speech data. Together, PhonBank and Phon meet most of the best-practice expectations for research in speech and language, including:

- compatibility across different computer platforms (Windows, Mac OS, Linux)
- full support to enter IPA characters, including the extended set of symbols and diacritics for clinical linguistics
- media linkage to transcripts (i.e., while viewing an utterance in the transcribed record, a user can click to play back the corresponding segment of audio and/or video)
- specialized methods for phonological data coding and analysis
- facilities for data sharing among scholars and clinicians, with the option to keep records private and secure as required by privacy laws and/or patient/family preferences
- free and open-source access

Previous descriptions of Phon and of the functions it offers can be found within the published literature,^{2,3,9} including in the area of phonological disorders.⁸ The present paper extends this documentation by focusing on the needs of practicing clinicians or clinical researchers, and on how current functions within Phon can be used to address these needs. Whenever relevant, we offer an outlook on functions currently being developed, many of which also center on current needs in clinical phonology.

CLINICAL ANALYSIS OF PHONOLOGY

When conducting an assessment of a child referred for atypical speech development, the speech-language pathologist aims to accomplish a number of goals simultaneously. First and foremost, the assessment aims to determine whether the child presents with a clinically significant speech delay or disorder, and whether he or she is a candidate for speech intervention services. A second goal is to describe the nature of any disorder, both with respect to severity and with respect to differential diagnosis of categories of speech sound disorder, such as primarily phonological versus primarily motor-based deficits.¹⁰ A further goal is to identify goals and targets for treatment, as well as to consider what treatment approach would be most appropriate for the child's needs. Lastly, the speech-language pathologist seeks to understand how the child's speech abilities interact with other domains of communication, including lexical and morphosyntactic knowledge.¹¹

A number of different types of assessment procedures (e.g., administration of a standardized test of articulation/phonology; elicitation of a connected speech sample; and stimulability testing) are considered necessary to achieve all of these objectives. It is important to keep in mind that Phon is a tool for the analysis of speech samples, rather than an instrument for their elicitation. (We refer the reader to previous work, notably the 2002 special forum in the *American Journal of Speech-Language Pathology* entitled "Perspectives in the Assessment of Children's Speech,"¹² for strategies to address the challenge of fitting all of the necessary components into the finite time available for assessment.) Thus, the primary goal of this section is

to provide a broad overview of methods used to analyze speech data after they have been obtained in a clinical assessment of child phonology. We group the analyses discussed below into three broad categories: independent analyses, relational analyses, and other analyses, such as intelligibility and consistency/variability. In later sections, we consider how Phon, either in its present state or in future versions, could facilitate the process of conducting these analyses.

Independent analyses

Independent analyses of child phonology aim to describe the child’s phonological system without considering whether his/her productions are correct relative to the associated adult target forms.

Phonetic inventory

The most fundamental independent measure is the phonetic inventory analysis, which aims to identify all of the speech sounds that the child produces as part of his/her spontaneous communication. A common criterion specifies that in order to be credited with a particular sound in his/her inventory, a child must produce that sound at least twice in a sample of spontaneous speech (e.g., Stoel-Gammon^{13,14}). The child’s speech production can then be analyzed with respect to the size of the inventory, as well as with respect to any sounds or classes of sounds missing from the inventory.^{13,15-18} In many cases, it is important to identify not only the overall inventory, but also inventories within specific positions in the syllable or word. It is well-established that children can exhibit positional asymmetries in speech sound production, such as children who produce velar place in final position but not in initial position.¹⁹⁻²³ In Table 1, we illustrate a positional phonetic inventory from a child with speech sound disorder, excerpted from McAllister Byun.²³

	Syllable-initial				Syllable-final			
	Labial	Coronal	Velar	Glottal	Labial	Coronal	Velar	Glottal
Nasal	m	n						
Stop	b	d		ʔ	p	t		ʔ
Fricative/affricate				h		s	ʃ	
Liquid/glide	w	j						

Table 1: Ben’s consonant inventory by position, age 3;9.27 (adapted from McAllister Byun²³)

Other inventories

The phonetic inventory can be distinguished from two other types of speech sound inventories: the phonemic inventory and the stimulability inventory.²⁴ The phonemic inventory starts from the phonetic inventory of sounds the child produces, but then goes a step further and determines which sounds can be used to produce meaningful minimal contrasts. For example, consider the case of a child who produces alveolar stops before all front vowels (e.g., producing [ti] for both “tea” and “key”) and velar stops before all back vowels (e.g., producing [go] for “go” and “dough”). In this case, the phonetic inventory would include both velar and alveolar stops, but the phonemic inventory would clarify that these sounds are not yet behaving as contrastive phonemes.²⁵

The stimulability inventory aims to identify the sounds that the child can produce under conditions more supportive than spontaneous speech. This might involve providing visual and/or

verbal models to facilitate sound production, or eliciting a sound in different phonetic contexts that might have a facilitative influence on production.²⁶

A final type of inventory aims to characterize the range of word and syllable shapes produced by a child speaker. The simplest measure is an inventory of all syllable shapes observed in a sample of spontaneous communication, represented as series of consonants and vowels (e.g., CV, CVC, CCV, etc.).²⁶ This inventory can be used to examine the diversity of syllable types produced, as well as any preferences for particular syllable shapes. Other measures identify syllable structure levels, ranging from Level 1 (simple vowels and CV syllables) to Level 4 (syllables including consonant clusters).^{27,28} This allows the clinician to quantify syllable complexity by calculating the proportion of syllables that belong to a given level, as well as the average complexity level in a sample.

Relational analyses

Relational analyses contrast with independent analyses in that they involve comparisons between the child's productions with their corresponding adult target forms.

Analysis of phonological patterns/processes

The most canonical type of relational analysis is the analysis of phonological patterns or processes, in which the clinician describes how adult target sounds and syllables are transformed in the child's productions. For example, a child with the phonological pattern of stopping produces stops in a context where the adult target form contains fricatives. Phonological patterns are commonly divided into processes of sound substitution (e.g., stopping or velar fronting); processes that affect syllable structure (e.g., cluster simplification or deletion of weak syllables); and assimilatory processes (e.g., consonant harmony or voicing of voiceless consonants in prevocalic position).²⁹ In addition to qualitatively describing the patterns that characterize a child's phonology, clinicians may calculate the rate of application of a phonological pattern.³⁰ These values can be further broken down by position (e.g., syllable-initial versus syllable-final) and by phonetic contexts. The analysis of phonological patterns is the most common way to identify treatment targets when adopting a phonological approach to intervention.³¹ Norms representing the appropriateness of different phonological patterns at different developmental stages are also widely used.³² Finally, several standardized measures of child speech incorporate analyses of the application of phonological patterns.^{31,33,34}

Measures of severity/complexity

In addition to being used to identify targets for treatment, relational analyses are commonly used to estimate the overall severity of a child's speech sound disorder. These summary measures can be computed repeatedly over time and represent a valuable way to track clinical progress. A widely used measure is Percent Consonants Correct (PCC).³⁵ To compute PCC, the clinician counts the number of consonants that the child produced in an adult-like fashion in a speech sample and divides this by the total number of consonants in the sample. (PCC is typically calculated from a sample of connected speech containing a minimum of 50 utterances.) In addition to the traditional PCC metric, clinicians and clinical researchers may use numerous variants such as PCC-Revised, in which distortions are not counted as errors, or Percent Phonemes Correct (PPC), which includes the accuracy of vowels as well as consonants.

Other relational measures provide slightly different information about the overall severity of speech sound disorder. Phonological Mean Length of Utterance (PMLU) is a measure that takes into account both a child's accuracy relative to adult target sounds and the length,

calculated in number of phonemes, of the child's productions.^{36,37} To calculate the PMLU of a word, the clinician scores one point for every speech sound (consonant or vowel) produced, adding another point for each consonant that was produced correctly relative to the adult target. PMLU can be averaged across all words in a sample to provide a summary measure. Percent Whole-Word Proximity (PWP) is a similar measure in which the child's PMLU score is divided by the PMLU associated with fully correct production. It has been suggested that overall PWP correlates with intelligibility, although this relationship has not yet been systematically established.³⁸

Other analyses of interest

Many other types of analysis have been proposed to characterize different aspects of children's speech productions. We address a few of the most central ones in turn in the next subsections.

Intelligibility

In addition to the standard independent and relational analyses of phonology described above, clinicians often undertake an assessment of the intelligibility of a child's speech. The optimal assessment of intelligibility requires some element of blinding, such as asking a listener unfamiliar with the child to write down his/her best guess of the identity of each word in a recording of the child's spontaneous speech. Overall intelligibility can then be estimated as the percentage of words correctly identified divided by the total number of words.³⁹ When a full assessment of intelligibility is not possible due to time constraints, clinicians may make an informal estimate of the child's intelligibility level (e.g., 50% intelligible in connected speech).⁴⁰

Consistency/variability over repeated productions of the same word

Another category of measures can be used to examine the consistency or variability of speech across repeated productions of the same word. These measures have seen increasing clinical use as a possible source of information regarding differential diagnosis of subtypes of speech sound disorder. A high level of variability across repeated productions might be seen as indicative of a deficit in phonological planning^{41,42} or in speech-motor planning.^{43,44} In the formalized inconsistency measure put forward by Dodd and colleagues,^{41,42} 25 target words are elicited three separate times over the course of one assessment session. Children whose attempts are transcribed in more than one way across the three repetitions in at least 40% of words are characterized as demonstrating "Inconsistent Speech Disorder." An alternative index of variability is the Proportion of Whole-Word Variation, or PWV.³⁷ To calculate PWV, the clinician identifies all cases in which a single word is attempted multiple times. The total number of forms produced is divided by the number of attempts, and this value can be averaged across all words in the sample that were produced more than once.

Measuring other aspects of spoken communication

Finally, the speech samples that a clinician collects in order to evaluate a child's phonology are often used to serve several additional purposes. The clinician may listen to the connected speech sample to screen for any abnormalities in the areas of voice, fluency, and resonance (e.g., hypo- or hypernasality).¹⁰ The same sample is often additionally used to analyze the complexity and accuracy of the child's expressive language production, including syntactic structure and morphology. It is now widely accepted that "speech" and "language" do not constitute truly distinct domains; they overlap, and children who have a deficit in one area are at increased risk for difficulties in the other as well.¹¹ Thus, any technology that can streamline the process of

conducting parallel analyses of speech and expressive morphosyntax can be of considerable clinical value.

USING TECHNOLOGY TO ANALYZE SPEECH ASSESSMENT DATA

In practice, it is rare for clinical phonological data to be analyzed with the full range of measures described above. Relevant data can be obtained from Skahan et al.'s survey of assessment practices self-reported by a sample of 333 pediatric speech-language pathologists in the United States.⁷ The most commonly used measure was an analysis of phonological processes, which just over 50% of clinicians reported that they “always” conducted. Phonetic inventories and phonological analyses of connected speech samples were “always” carried out by a smaller proportion of clinicians (36% in each case). Constraints on clinicians' time, which stem from both heavy caseloads and extensive requirements for documentation, are widely recognized as an important factor limiting the number and depth of analyses carried out.³⁴

Skahan et al. observed that “technology is frequently posed as an answer to the time constraints involved in SSD assessment” (p. 252); however, these promises have yet to bear fruit in practice, with only 8% of their survey respondents indicating that they ever made use of computerized analysis procedures. Possible reasons for the limited uptake of computerized approaches to assessment and analysis were posited to include a lack of access to computers in the clinical setting, a lack of familiarity with technology or with the available assessment programs, and the high cost of some software programs. Barriers pertaining to the availability and familiarity of technology have certainly become lower since Skahan et al. conducted their survey in 2007 and, as an open-source software, Phon is and will always be available free of charge. In the sections that follow, we detail functions available within Phon to facilitate the analysis of clinical phonological data.

PHON-ASSISTED METHODS FOR PHONOLOGICAL ANALYSIS

Virtually all of the analyses described above can be streamlined through the use of Phon software, potentially saving hours of time while providing empirical documentation for future verifications, comparisons, and analyses. Below we describe in detail how each analysis can be carried out in Phon. As a first step, however, it is necessary to enter the child speech samples into Phon. A body of speech data stored in Phon is termed a corpus (plural corpora). Although this term evokes a large sample of data spanning multiple points in time, a corpus can be as small or as large as the user desires. The most typical corpus includes a media recording of child speech (audio and sometimes video) and the corresponding orthographic and phonetic transcriptions. However, in cases where the user favors a pen-and-paper approach to data collection, or the media recordings have been lost or corrupted, it is also possible to create a Session transcript without linking it to a media file. It is important to note at this juncture that *creating* a corpus in Phon is distinct from *sharing* a corpus via PhonBank. The corpus a user creates is saved only to his/her local machine and is not accessible to outside viewers. Should the user later pursue the data sharing option, the corpus will be made available to the research community through an independent web server.

Creating a new project within Phon

Phon data are organized into three main components: the Project, the Corpus, and the Session. Upon first launching Phon, the program sets the location (folder or directory) where Phon data will be stored; this is referred to as the PhonWorkspace. This default location can be later modified by the user. Data are stored within one or more Project folders, which in turn contain at

least one Corpus folder. The Project folder also contains a unique “project.xml” file, sister to the Corpus folder(s); this file is automatically generated and managed by Phon, and must remain in this location. Finally, each Corpus folder contains one or more Session files, in which transcription data are stored. Session files are documents in XML format; they must be opened and edited from within Phon itself.

Both the Workspace and the Project Manager window are illustrated in Figure 1 below. This sample Workspace lists five different projects. Of these, the Dutch-CLPF project is represented within the Project Manager in Figure 2. The left column in the Project Manager lists 12 different corpora, each representing a different child. The corpus of the child Eva has been selected; thus, the right-hand column displays a list of all Session transcriptions pertaining to this corpus. Each Session contains a transcribed record from a time point in Eva’s longitudinal development. By double-clicking an item in this list, the user can open a Session transcript.

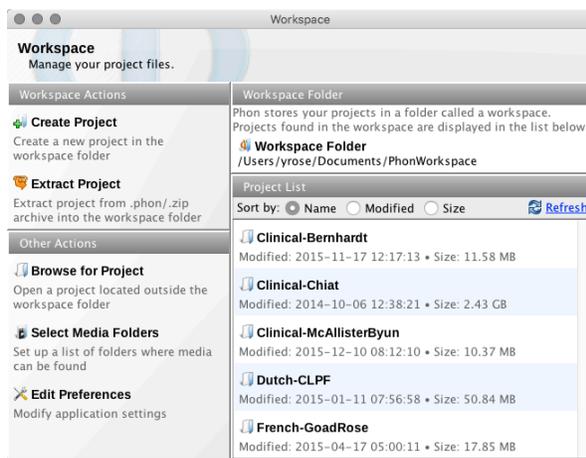


Figure 1: Workspace

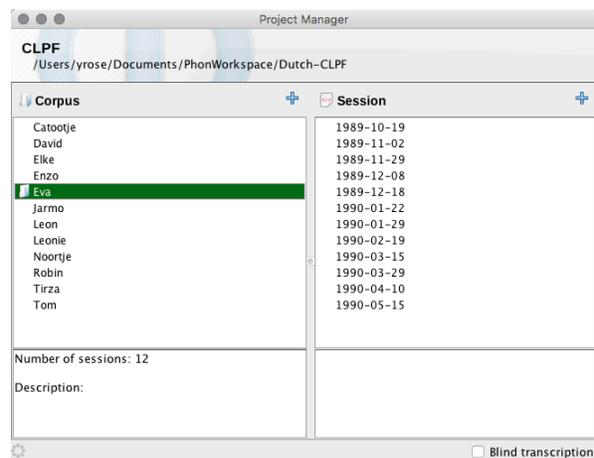


Figure 2: Project Manager

In practice, the organization of a Phon project will depend on the needs of the user. A researcher documenting the longitudinal development of a cohort of children may create a Project folder containing one Corpus folder for each child in the study. These Corpus folders would contain one Session file for each point in time at which data were recorded for that child. A researcher conducting a cross-sectional study might group all the Session files of a given cross-section within a Corpus, with as many Corpus folders as there are cross-sections involved in the study (Project). For clinical purposes, a Phon user may wish to create one Corpus folder for each child on the caseload. Alternatively, the Corpus folder could represent a type of assessment task (e.g., Connected Speech Samples), or a period of time (e.g., Assessments Fall 2015).

The creation of Project, Corpus, and Session folders is supported through Phon’s graphical user interface, with some functions available through the Workspace and others through the Project Manager. Further detail about these and other functions of Phon are documented in the user manual, which can be accessed through the program’s Help menu. Tutorial videos are also available through the Phon website (<https://www.phon.ca>).

Data collection and media segmentation

Given the ready availability and user-friendliness of digital audio and video recorders, Phon does not incorporate functions for media recording. However, it does contain media players for both

audio and video content. One of the most useful functions of Phon is segmentation, a process that links time intervals from stored media to transcription records, so that when viewing the transcribed record of an utterance, the user can click to play back the associated media. Media files in all commonly-available formats (e.g., wav, aif, mp3, mp4/H.264) can be uploaded to a folder that the user has designated as the Media Folder. When a Session file is created, the user can link it to a specific file in the Media Folder using options in the Session Information view panel.

The process of media segmentation depends on the nature of the data being entered, for which there are two major scenarios. In the first case, the recorded data do not follow a specific structure or template, and the user does not have a pre-existing transcript (either orthographic or phonetic) of the utterances in the sample. This is the typical scenario in naturalistic studies of child development; it is also characteristic of spontaneous speech samples elicited in the clinical setting. In the second scenario, the user has a pre-existing record of the target utterances that make up a recording. This case applies to most standardized speech measures, including single-word picture naming tests like the *Goldman-Fristoe Test of Articulation*.⁴⁵ Since the ideal clinical assessment includes samples of both structured and unstructured speech, we review the media segmentation process for both types of recordings.

Unstructured (spontaneous) approach to data elicitation

Unstructured speech samples allow the clinician or researcher to evaluate both segmental and prosodic aspects of the child's speech in connected utterances, which tend to be most representative of the child's ability to communicate in real-life settings.⁴⁶ A drawback of the unstructured speech sample is that analysis may require a nontrivial investment of time on the part of the clinician or researcher.⁴⁷ In the specific context of Phon, spontaneous samples cannot be analyzed using pre-formatted transcripts or templates, which adds one step to the overall data processing routine.

Consider the case of a clinician who has just recorded a connected speech sample and wishes to create a linked transcript of this sample in Phon. The user begins by uploading the recording to the folder that he/she has specified as the Media Folder for this Phon Project. In the Phon Project Manager, the user can navigate to the relevant corpus and create a new Session file, name the file, and link it to the appropriate media file through the Session Information view panel. The user can now proceed with media segmentation. For unstructured recordings, the segmentation mode must be set to "Insert record after current one," which is the default option in the Segmentation interface in Phon (accessible via the View menu within the Session Editor).

To segment a sample, the user begins by listening to the recording and uses a simple keystroke or click (as specified within the Segmentation view panel) to enter a marker each time he/she hears an utterance by the child. For each marker the user enters, Phon generates a record associated to a time interval spanning back a set amount of time from the point the user indicated. After a rapid first pass to tag all of the utterances of interest, the user can go back and refine the durations of the automatically generated windows to align more closely with the child's utterances. The units tagged can be as long or as short as the user needs; three seconds is typically used to segment child utterances.

At the end of the segmentation process, the user has an annotated version of the media file that is easy to navigate; a simple click or keystroke will advance to the next utterance of interest, skipping over any silences or non-target utterances such as comments from the clinician. This can

greatly expedite the process of orthographic and IPA transcription, which we describe in detail in subsequent sections.

Structured approach to data elicitation

If the speech task features a specific set of words elicited in a structured (predictable) order, it is possible to expedite the data preparation process by creating a pre-transcribed Session file to serve as a template. Clinicians and clinical researchers can derive significant time savings by creating templates for any single-word picture naming test or other standardized speech elicitation tasks that commonly form a part of their assessment protocol. For example, a clinician who regularly uses the *Goldman-Fristoe Test of Articulation* can save a session template containing one record for each item in the *Sounds-in-Words* subtest of the *GFTA*. To maximize time savings, the pre-entered information can include both the orthographic transcription and corresponding IPA transcription(s) of each item. Whenever the user wishes to segment a recording of the *GFTA Sounds-in-Words* subtest, he/she can do so by duplicating the Session template through the available contextual menu and giving the duplicate file a new name in the appropriate Corpus folder, as illustrated in Figure 3 and Figure 4.

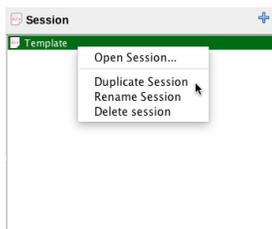


Figure 3: Duplicate Session template

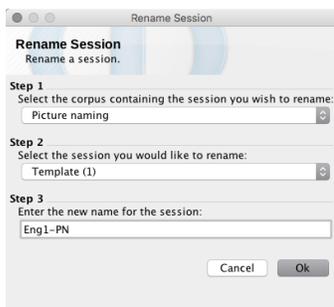


Figure 4: Rename Session template

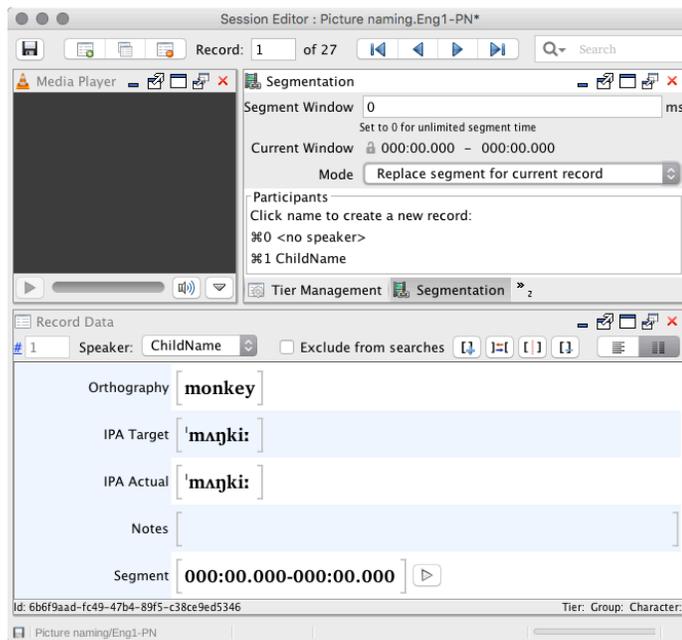


Figure 5: Segment pre-transcribed Session

The process of media segmentation can then proceed in essentially the same manner as described in the preceding section. However, it is essential in this case that the mode of segmentation be set to “Replace segment for current record.” When using this template-oriented mode of segmentation, Phon automatically switches to the next record after the current one is identified by the user. For example, in Figure 5, the pre-entered transcript indicates that the child’s upcoming utterance is expected to be the word ‘monkey.’ Immediately after hearing this word, the user activates the segmentation command with a click or keystroke, and Phon marks off the time interval roughly corresponding to this production. It then automatically advances to the next record in the transcript (e.g., ‘banana’), and the user repeats the segmentation command on hearing this target word. In short, with a pre-saved template, the user simply needs to listen to the

recording and time-stamp each utterance to link it to the corresponding transcribed entry. The tagged intervals can then be refined as described above. Both modes of segmentation are summarized in Table 2.

Data collection	Unstructured	Structured
Session file	New/empty Session	Pre-transcribed Session template
Segmentation mode	Insert record after current one	Replace segment for current record

Table 2: Data collection and approaches to data segmentation in Phon

Entering data in Phon

The task of transcribing data for phonological analysis remains one of the most time-consuming parts of any phonological assessment. A possible solution that often comes to the mind of the time-conscious individual is to transcribe only the sounds that are produced in error. By citing error sounds outside of their larger context, however, this approach may make it harder to identify the source of the error pattern. For example, consider a child with a phonological pattern of consonant place harmony who produced [gʌk] for *duck*. Recording this error as /d/ ↔ [g] misses the fact that the child does not have a problem producing /d/ per se; rather, the child has difficulty producing words containing multiple consonants that differ in place of articulation. Thus, a maximally transcribed dataset creates the best opportunity to identify the true nature of a child’s phonological patterns, and therefore to optimize target selection and intervention planning. Phon provides tools to help users transcribe samples as completely as possible with a minimum of additional effort. Chief among these tools is a built-in dictionary containing the target IPA for an extensive range of words spanning several languages and dialects (including North American and UK English), along with an “auto-transcribe” option that automatically populates orthographically transcribed entries with corresponding IPA forms. A clickable map for easy IPA character entry is also provided. Following the same structure as above, we describe these tools in the context of both unstructured and structured data recordings. In either case, as soon as the transcriptions are completed, the user is only minor verifications away from obtaining all analyses available within Phon.

Transcribing unstructured datasets

After segmentation, freely-produced utterances must be transcribed orthographically. This involves reviewing the tagged utterances one by one and entering the words the child produced in the Orthography tier. Unintelligible utterances can be marked with two codes: “xxx” is used in to make speech that is both unintelligible and left untranscribed; “yyy” indicates that the unintelligible production will be phonetically transcribed.

Although orthographic transcription can be time-consuming, it enables the user to take advantage of one of the most important time-savers in the Phon toolkit: an IPA Lookup function that automatically enters the IPA transcription of the expected (adult-like) pronunciation based on the orthographic record. Figure 6 shows a Phon record in which the IPA Target tier has been completed using the IPA Lookup function (right-hand window in Figure 6). It is possible to use this function to fill in the IPA Target tier on a record-by-record basis. A more time-saving option is to populate all records in a session at once using the Auto-transcribe function.

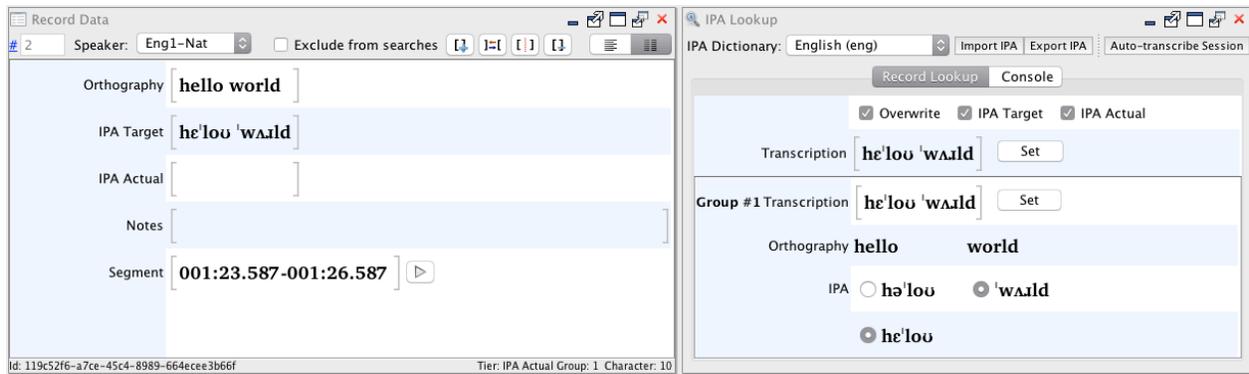


Figure 6: IPA Lookup and automatic IPA transcription

The final tier, IPA Actual, contains IPA transcriptions reflecting what the transcriber perceived as the child’s actual output. This tier can be completed in various ways. The user can enter the phones he/she hears, using keystrokes for those sounds that are the same in orthography and IPA (e.g., /p,b,m,i,e/) and using Phon’s built-in IPA map to enter special IPA characters (e.g., /ʃ,ʒ,ŋ,ɛ,ə/). As a potentially time-saving alternative, users can further exploit the IPA Lookup function to populate both the IPA Target and the IPA Actual tiers at once. We discuss this method further in the context of structured datasets below.

Transcribing structured datasets

As discussed above, when a task elicits a known list of words in a predictable order (as in the case of a standardized picture-naming test), users can streamline the transcription process by using pre-populated Session templates. Templates typically contain transcriptions in the Orthographic and IPA Target tier; many users also prefer to also have the IPA Target tier pre-transcribed. This approach is more efficient in that the user does not need to transcribe any sounds that the child produced in a target-like manner; it is only necessary to adjust the existing transcription to reflect any deviations from the target. (The *Hodson Computerized Assessment of Phonological Patterns*, which features a similar task of modifying computerized IPA transcriptions to reflect deviations in the child’s output, is estimated to require only 10 minutes for data entry.¹⁰) A potential drawback of this method is that the presence of a pre-transcribed form can introduce some bias. For a vowel sound produced with some degree of distortion, for example, a user may be more likely to note the deviation when transcribing the complete utterance than when a pre-transcribed vowel is provided. However, transcribing from scratch is not only more time-consuming, but also imposes higher demands on the user’s attentional resources. Thus, we contend that using Phon to generate a maximally-transcribed record and then making only those modifications needed to match the child’s output is likely to represent the optimal solution in terms of both efficiency and accuracy.

Analyzing data in Phon

Syllabification and alignment of IPA transcriptions

Phon contains specialized algorithms that automatically assign information about the syllable position of each sound in a transcribed word. (Because syllabification differs across languages, and given that different researchers or clinicians may use different approaches to syllabification even within a language, the user has the option to choose among several different syllabification

algorithms.) As illustrated in Figure 7, syllabification is represented through color coding: blue for onset, red for nucleus, and green for coda position.

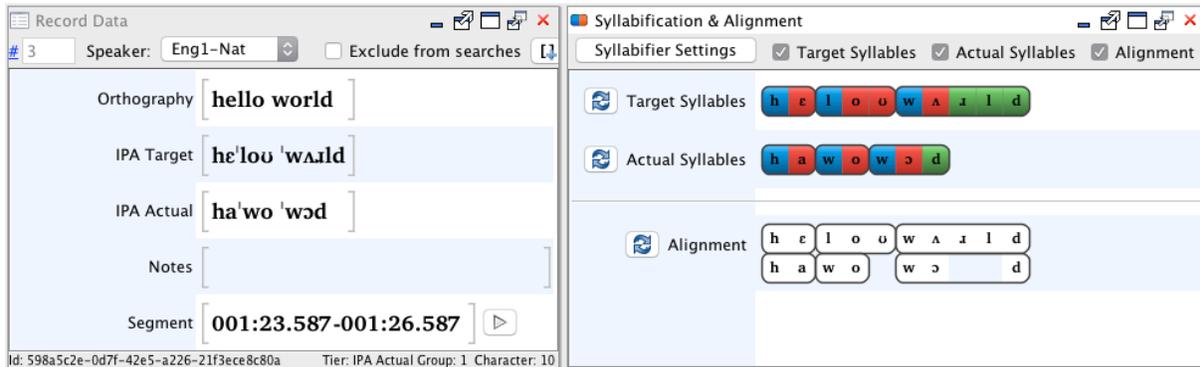


Figure 7: Syllabification and alignment of IPA Target and Actual forms

Phon also performs pairwise, phone-by-phone alignments between IPA Target and Actual forms, so that specific segments in the child’s actual output can be compared with corresponding segments in the target form. These alignments are represented in the form of vertical mappings, as seen in Figure 7, under the color-coded syllabification annotations. However, some level of uncertainty is inevitable in this type of analysis. For example, if a child produces [təməsməʊ] for “Thomas small,” should the single [s] be aligned to the coda of *Thomas* or the onset of *small*? The user may thus disagree with the output of the automated algorithm at times, especially in cases where the target and actual forms differ considerably. In such cases, the user is free to modify the alignment annotations through the graphical interface, simply by clicking on the misaligned phone and dragging it to the desired position.

Data queries

Phon offers a number of flexible methods to query a given dataset. Queries can be used to focus in on relevant subsets of the data, which could involve different points in time (e.g., sessions before the age of 2;0); individual lexical forms (e.g., occurrences of the word *cat*); or different target phones (e.g., all instances of /k/). Each method is available through a graphical query form, which the user can specify using minimal *textual*, *regular*, and *phonological* expressions. Textual expressions, which consist of strings of orthographic or IPA characters (e.g., a search for /k/ returns all utterances containing that phone), are the simplest to use but also the most limited. Regular and phonological expressions allow more powerful tools such as wildcards, which are special characters for pattern matching; the expression “play.*” will return various forms including ‘play, plays, player, ...’. In addition to wildcards, phonological expressions make use of specially developed phonological codes; a search for a specific phonological feature or features, represented in set notation, would return all strings that match that featural description. For example, a search for {labial} would return all utterances containing a segment with the labial place of articulation, such as /p,b,m,f,v,w/, while the query {labial, obstruent, voiced} limits these results to the voiced labial obstruent consonants /b,v/. Using phonological expressions, phones and feature sets can also be combined with references to syllable positions (e.g., ‘o’ for onset; ‘c’ for coda). For example, the phonological query “{coronal, fricative, voiceless}:o” returns occurrences of [θ, s, ʃ] found in syllable onsets. The full set of descriptive features and phonological markings used in Phon is provided in the user manual.

Used in combination, these query functions provide a flexible, powerful suite of tools for phonological data mining. Most of these functions can be learned within minutes, and Phon offers a large degree of flexibility with regard to descriptive features; for example, /t/ can be identified by queries using either the feature {coronal} or the feature {alveolar}. However, many of the measures commonly used in clinical research and practice, particularly relational analyses and variability measures, involve a high level of complexity. To address these needs, automated tools for clinical analysis have been added to Phon. We describe these (and forthcoming) tools in subsequent sections. Before we turn to this topic, we first describe data reporting within Phon.

Data reports

In its current version, Phon produces three main types of reports, each of which can be saved as a CSV data file. CSV stands for ‘comma-separated value’, which is a standard format to write text files, which can then be opened within spreadsheet applications such as OpenOffice/LibreOffice Calc or Microsoft Excel. (Note that to correctly display IPA characters in Microsoft Excel, the CSV files have to be imported as Unicode UTF-8 external data text sources, rather than being opened directly as simple text files; see Phon’s user manual for more information.) While this format may not be the most familiar to clinical users, CSV is the most widely compatible format for processing the results of analyses in third-party applications. In addition, the user can always copy the content of result tables generated by Phon and paste them directly into other applications’ documents.

The three main report types generated by Phon are Result Lists, Inventories of Results, and Assessment Results. We defer discussion of this last type until the next section on clinical data analysis in Phon. A Result List displays the full set of outputs returned in response to a query entered by the user. For example, Figure 8 shows a Result List returned in response to a query for utterances containing the segment /l/ in the IPA Target form. The “Result” column indicates how the target segment changed between the IPA Target and the IPA Actual forms, presented alongside the corresponding orthographic, IPA Target, and IPA Actual transcriptions. The user is free to include or exclude these columns as desired, which provides an easy means to extract and share informative subsets of the full database. Result Lists can extend and enhance the user’s qualitative analysis of a dataset, since they make it easy to compare the behavior of a particular target phone across a range of production contexts.

Inventories of Results, which are distinct from the phonetic/phonemic inventories used clinically, consist of counts of the number of times a given result (e.g., a target-actual phone pair such as /s/ ↔ [t]) was observed in a session transcript. Figure 9 provides an example of an inventory of mappings in a child’s attempts to produce the target phoneme /l/, aggregated across five session transcripts; the child’s age is listed at the top of each column.

Result	Orthography	IPA Target	IPA Actual
l ↔ Ø	play toys	'pleɪ 'tɔɪz	apa tɔɪ
l ↔ w	look at this	'lʊk 'æt 'ðɪs	wʊkɪ jə zɪs
l ↔ Ø	two plates	'tu: 'pleɪts	dʊ pet
l ↔ j	silly	'sɪli:	sɪji

Figure 8: Result list

	02:00	02:01	02:02	02:03	02:04
l ↔ d	0	0	0	1	0
l ↔ j	2	4	7	3	1
l ↔ l	5	8	17	32	28
l ↔ w	6	6	2	3	1

Figure 9: Aggregated inventory

The inventory of results can be used to calculate the percent application of a given mapping at a given point in time, and to track changes in this rate of application over time. These inventories are central to the description of trajectories of phonological development in the context of

longitudinal studies. As the use of Phon expands to the clinical setting, these same inventories can provide a useful way to quantify and visualize progress over the course of intervention.

ANALYZING CLINICAL DATA IN PHON

Dedicated tools for clinical data

As already mentioned in introduction, in a concerted effort to increase the clinical utility of Phon, over the past two years the Phon team has added automated functions corresponding to several of the most widely used clinical analyses. These functions can also be combined with queries, enabling the user to restrict analyses to a particular subset of the corpus data. In many cases, there are ongoing plans to make these functions more user-friendly by developing pre-specified query forms and customized output reports. Tools that currently exist but may undergo further refinement are listed in Table 3 and described in the next three sections; a final section describes tools that have not yet been implemented but will be added in a future version of Phon.

Function	Description
Phone Inventory	Inventory of phones attempted Inventory of phones produced
Phone Accuracy	List of each phone attempted, with counts for accurate productions, substitutions, and deletions; percentages can be easily derived in third-party applications
Word Match	Measures of accuracy at the level of phones, consonant/vowel categories, and stress, based on Bernhardt et colleagues ^{48,49}
PCC/PVC (Percent Consonant/Vowel Correct)	Measures of consonant/vowel production accuracy, based on the original work by Shriberg et colleagues ³⁵
PMLU (Phonological Mean Length of Utterance)	Measure of phonological productivity, as originally defined by Ingram ³⁷ and further refined by Arias & Lleó ⁵⁰

Table 3: Clinical analyses currently implemented in Phon, available through the Tools menu

Tools for independent analyses

The current version of Phon includes functions to facilitate the process of extracting a phonetic inventory. As described above for general phonological queries, phonetic inventories can be restricted to specific positions using the syntax illustrated in the screen shot in Figure 10. The query expression “\c:o”, means “any consonant in onset position,” whereas “\c:c” would return a corresponding inventory in coda position. Options within the Syllable Filter allow the user to narrow the search in other ways, such as by considering only monosyllabic words or only the initial syllable of multisyllabic words.

Figure 10: Consonant inventory (word-initial onsets)

Inventories extracted through this function also provide a count for each of the attested phones. These counts are useful if the user wishes to apply a numerical criterion, such as the common clinical requirement that sounds be produced two separate times in order to be considered part of the child’s inventory.^{13,14} Depending on the size of the available speech sample, the user may wish to use a higher or lower cut-off point. Phon also makes it possible to extract inventories based on IPA Target forms, yielding a list of all phones contained in the target words attempted by the child. These lists and their corresponding counts can be used to examine whether a child appears to be favoring or avoiding words that contain certain sounds. This type of inventory can be extracted by adjusting the Search Tier selection at the top of the interface depicted in Figure 10.

Tools for relational analyses

The most basic relational analysis currently available in Phon is the Phone Accuracy tool. Using this function, Phon reports the number of times each phone attempted by the child is produced accurately, substituted, or deleted. While this measure is relatively broad, it provides a general assessment of the segments that are mastered and/or problematic for the child. In addition, a dedicated function for PCC calculation has been implemented in Phon, as illustrated in Figure 11. As the figure shows, Phon derives a PCC value for each individual utterance. However, most clinicians use PCC as a summary measure computed across a set of utterances. This can currently be achieved by saving the PCC results to a CSV file, opening them in a spreadsheet and/or statistical software package, and calculating summary values such as the mean and standard deviation.

Orthography	IPA Target	IPA Actual	# Target	# Attempted	# Correct	# Deleted	% Correct	% Deleted
here	hɪ	hiə	2	2	2	0	100	0
plate	plɛt	pɛt	3	2	2	1	67	33
goldfish	gɒldfɪʃ	gɒftʃ	5	3	3	2	60	40
help	hɛlp	hʌ	3	1	1	2	33	67

Figure 11: PCC results

Finally, the current version of Phon includes a PMLU analysis that follows similar logic: it automatically extracts both PMLU and related Percent Whole-Word Proximity measures, which can be both visualized directly within Phon and further processed in third-party applications according to the user's needs.

If the user is interested in analyzing the application of phonological processes, the query functions described above can be used to identify and quantify relations between pairs of target and actual phones produced. For example, to determine whether a child exhibits any instances of stopping, the user can select the Query menu, initiate a Phones query, and specify a search for utterances in which the IPA Target tier contains a fricative and the aligned segment in the IPA Actual tier contains a stop. Table 4 presents possible query terms that can be used to search for any of a widely used range of phonological processes, many of which overlap with the list of phonological processes identified within the *Khan-Lewis Phonological Analysis*.³⁴ (In Phon, descriptive features are listed between braces, and “-” means ‘not’.) A list of all outputs observed in connection with a particular target segment, as seen in Figures 8-9, can be used to calculate the percentage of application of a given phonological pattern identified through these queries. In all cases, the search for phonological processes can be narrowed to a specific position within the syllable by adding “:o” for onset or “:c” for coda.

Phonological process	IPA Target contains	IPA Actual contains
Stopping	{fricative}/{continuant}	{stop}
Gliding/vocalization	{liquid}	{glide}/{vowel}
Deaffrication (to stop/fricative)	{affricate}	{-affricate}
Velar/palatal fronting	{velar}/{palatal}	{coronal}
Coronal backing	{coronal}	{velar}
Voicing/devoicing	{voiceless}/{voiced}	{voiced}/{voiceless}
Glottalization	{-glottal}	{glottal}
Lateralization	{-lateral}	{lateral}

Table 4: Phon queries to identify segmental substitution processes

All of the examples listed in Table 4 represent phonological patterns of substitution. Phon queries also support the detection of assimilatory patterns such as consonant harmony, as well as syllable structure processes of deletion, epenthesis, and metathesis. Interested readers may consult the Phon manual for more information on how to use these functions, also available through the Query menu.

Users who wish to examine syllable structure processes in more detail can analyze one or more transcribed samples of the child's speech using Phon's Word Match analysis. The output of this analysis reports the syllable shape and word stress of all target word forms in conjunction with systematic segment, syllable, and word stress comparisons between these and the child's productions of these forms, as illustrated in Figure 12. (The output of the Word Match analysis also provides a convenient aggregation of syllable shapes produced that can be used to generate an inventory of syllable shapes, an independent analysis.)

Orthography	IPA Target	IPA Actual	Exact Match	IPA Target CV	IPA Actual CV	CV Match	Target Stress	Actual Stress	Stress Match
got	gɒt	dɒ?	FALSE	CVC	CVC	TRUE	U	U	TRUE
books	bʊks	bʊks	TRUE	CVCC	CVCC	TRUE	U	U	TRUE
cartoons	kɑːˈtʊnz	tɑːˈʔunz	FALSE	CVˈCVCC	CVˈCVCC	TRUE	U1	U1	TRUE
like	laɪk	laɪ?	FALSE	CVVC	CVVC	TRUE	U	U	TRUE
tiger	ˈtɪɡə	ˈtɪɡə	TRUE	ˈCVV.CV	ˈCVV.CV	TRUE	1U	1U	TRUE
because	bɪˈkɔz	ˈaɪtəz	FALSE	CVˈCVC	ˈVV.CVC	FALSE	U1	1U	FALSE
kangaroo	ˌkæŋɡəˈjuː	ˌtæŋɡəˈjuː	FALSE	CVC.CVˈCV	CVC.CVˈCV	TRUE	2U1	2U1	TRUE

Figure 12: Word Match results

Tools for other analyses

Clinicians and researchers agree that intelligibility is important to measure, since it can predict how much difficulty a child will have communicating with teachers or peers in real-world settings. Changes in intelligibility can also serve as a valuable marker of progress over time.⁵¹ However, as noted above, valid measures of intelligibility can be time-consuming and also generally require that the clinician enlist an outside assistant. As a consequence, many speech-language pathologists simply give an impressionistic estimate of a child’s intelligibility (e.g., 80% intelligible in connected speech). Unfortunately, such estimates have low reliability and questionable validity.⁴⁰ Phon offers an interface for blind transcriptions and consensus-based validation of the blind transcripts. While it is not a complete solution, we hope that this improved interface will encourage more clinical practitioners and researchers to incorporate rigorous, blinded measures of intelligibility into their assessments.

FUTURE DIRECTIONS AND CONCLUSION

In addition to refining and further automating the analyses described above, future versions of Phon will incorporate new tools developed specifically for the purpose of clinical data analysis. Many of these replicate functions that were originally available through PROPH+ (the Profile of Phonology module of the Computerized Profiling system).^{52,53} PROPH+ has not been updated in over a decade and now lacks compatibility with current operating systems. The original authors of this program have generously given their permission for the reimplementation of PROPH+ analyses within Phon. These will include additional inventories of phonological units and processes, as well as expanded approaches to PCC and segmental accuracy measures.

Word shapes (by consonant/vowel)	Percent Consonant Correct: all
Word shapes (by number of syllables)	
Word shapes (by stress patterns)	
Syllable shape modification	place of articulation
Syllable deletion	manner of articulation
Target consonant production	clusters
Target vowel production	Segmental Accuracy: accurate productions
	substitutions
	deletions

Table 5: Forthcoming automated analyses (including refinements to existing functions)

In addition, the PROPH+ program included algorithms to quantify variability and homophony within a given dataset. Variability is identified if a single orthographic target word, e.g., *pasta*, is produced in more than one way (e.g., [patə], [batə]) within a single recording session. Following a similar logic, homophony would be detected if two distinct target words, e.g., *pasta* and *basket*,

were produced by the child with the same output form (e.g., [patə]). Given the increased importance of variability analyses in diagnosis and treatment planning, as discussed above, these functions will be valuable additions to Phon's clinical tool kit.^{41,42}

Conclusion

We saw above that technological advances have often been held out as the solution to problems of time constraints on the clinical assessment and analysis of phonology, but these promises have not yet had a widespread or lasting impact on clinical practice. We expressed our hope that Phon, as a powerful tool that is available for free, will help overcome some of the barriers that have limited previous approaches. Barriers pertaining to comfort with technology will naturally lower over time as a generation of digital natives enters clinical practice. The major remaining challenges include (1) raising awareness of the availability and utility of the tools described above, and (2) convincing overworked clinical practitioners that learning and using Phon is a worthwhile investment of their limited resources of time. We wish to emphasize that adopting Phon is not so much a question of adding time to the assessment and analysis process, but of making an up-front investment of time that will pay off by saving time in the areas of diagnosis, goal setting, and report writing. The main time requirements imposed by Phon involve data entry, namely media segmentation, orthographic transcription (which is unnecessary in the context of structured elicitation tasks), and modification of auto-populated IPA forms to match the child's actual output. Once the data have been entered, a wide range of analyses is available within only a few clicks. Given current development plans, the range of analyses relevant to clinical phonology is also set to increase significantly. As third-party payers increasingly call for concrete evidence of improvement to justify continuing service provision, the quantitative information provided by Phon offers an important asset.

We also contend that the tools provided by Phon not only make clinical analyses more efficient, they also make them more effective. In their coursework on phonology, most speech-language pathologists learn the importance of considering the influence of hierarchical or nonlinear influences on child phonology.⁵⁴ For example, a child may delete segments only when they occur in word-medial coda position. If the user's analysis does not take positional information into consideration, this systematic pattern may be overlooked, and the user may conclude that the child has a pattern of segmental deletion that applies sporadically. Despite the importance of this information for identifying treatment targets, fewer than 20% of speech-language pathologists in a 2013 survey indicated that they ever made use of a nonlinear approach to intervention for children with speech sound disorders.⁵⁵ This suggests that nonlinear or syllable-structure-based analyses will not achieve widespread uptake in clinical practice unless they can be made more user-friendly and time-efficient. Phon's automated method for syllabification, along with the ability to narrow the search for a phonological pattern by position within the syllable and word, represents a first step toward addressing this challenge.

We close with a note on data sharing, which is a core principle of the mission that produced the CHILDES and PhonBank databases and Phon software and is strongly encouraged by most public funding agencies. While often relegated to footnote status in the published literature, data sharing plays a vital role in expanding our collective understanding of speech and language. Many clinical practitioners will not feel comfortable sharing data, and they are under no obligation to do so. However, we encourage clinical researchers and/or practitioners in a setting with an Institutional Review Board to investigate the possibility of obtaining parent consent and child assent for data sharing. Parents are often highly motivated to take steps that will advance

research in speech development and disorders and hopefully help other children with speech disorders. Through data sharing, we hope to expand the breadth of clinical samples available for research, so that researchers can investigate clinically relevant hypotheses without first taking a year or more to create a new corpus. We also hope to improve interventions by making it easier to collect systematic, quantitative measures to document individuals' response to treatment over time. Finally, it is also our hope that a shared tool like Phon can serve as a bridge to enhance communication between researchers and practitioners in the area of speech development and disorders.

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