

Applications of learnability theory to clinical phonology

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Abstract

This paper provides a tutorial on the selection of complex target sounds for treatment following from known principles of language learnability. The focus is on syllable structure in recommending onset consonant clusters for treatment. The step-by-step procedure of cluster selection is illustrated for one child, Jarrod, who presented with a phonological disorder. Target selection procedures are guided by universal principles that govern the phonotactics of onset clusters and experimental evidence that supports the efficacy of phonologically complex targets. The prediction is that treatment of onset clusters will facilitate Jarrod's learning of both complex and simple properties of the sound system.

Keywords: *Phonological complexity, consonant clusters, phonological disorder, learnability theory.*

Introduction

One goal of learnability theory is to identify how linguistic input influences children's learning of a target language, albeit syntactic, semantic or phonological properties of grammar (e.g. Pinker, 1995). The aim is to model the effects of language learning through logical, mathematical, statistical and computational manipulations (e.g. Matthews & Demopoulos, 1989; Pinker, 1984; Tesar & Smolensky, 1998; Wexler & Culicover, 1980). For the most part, these endeavours have resulted in formal arguments about the quality and quantity of input that is needed to promote the language acquisition process. The main contribution of studies of language learnability has been to the advancement of linguistic and acquisition theories. This is perhaps most notably exemplified in the works of Chomsky, Gleitman, deVilliers, Wexler, Pinker, and Smolensky for typical development. However, there are practical applications of learnability theory that are coming to the clinical forefront (for review, see Gierut, in press). These are of special importance in the treatment of children with phonological disorders.

Children with phonological disorders have impoverished productive sound systems that are characterized by reduced segmental inventories relative to the target grammar. These children appear to have few, if any, concomitant lags in auditory, motor, linguistic, cognitive or social development (Shriberg, Kwiatkowski, Best, Hengst, & Terselic-

Weber, 1986; cf. Camarata & Schwartz, 1985; Chiat, 1994; Hoffmann, 1992). This notwithstanding, phonological lags have the potential to negatively impact children's long-term communicative development by affecting skills like reading, writing, spelling or math, all of which are necessary for success in academic settings (Bird, Bishop, & Freeman, 1995; Felsenfeld, Broen, & McGue, 1992). The real challenge in the study of children with phonological disorders is to identify the most efficient and effective way to promote phonological learning so as to quickly bypass, or at least accommodate the potentially adverse consequences (Shriberg, Gruber, & Kwiatkowski, 1994). Phonological treatment is a means to this end, with learnability theory being one approach that provides direction about the optimal course of intervention. In this regard, there is a growing body of evidence to suggest that the presentation of complex input in treatment enhances widespread generalization learning across the phonological system, thereby improving treatment efficacy (Gierut, 2001, for review). Complexity holds much promise because it is thought to be a hallmark characteristic of learning in general, and may emerge as the unifying property that crosscuts various populations and methods of intervention in particular. Complexity approaches to treatment efficacy (coined CATE in some areas of study, e.g. Thompson, Shapiro, Kiran, & Sobecks, 2003) may enhance learning across ages, clinical populations, and linguistic and nonlinguistic

disorders. Complexity also aids in differentiating the effects of treatment efficacy from treatment outcomes (Morrisette & Gierut, 2003; Rvachew & Nowak, 2001; 2003). It has the potential to help identify which factors are integrally related in treatment as opposed to those that are not (Gierut, in press). The implications of complexity are far reaching, and the interested reader may turn to a recent set of tutorials for further information (Barlow, 2004; Gierut, 2001, 2004). Given this, we evaluate the clinical case of "Jarrod" from a learnability perspective.

Jarrod is a 7;0 year old boy, with a complicated and multifaceted developmental and linguistic history that may or may not be due to an organic cause (Holm & Crosbie, 2006). This case was selected for its diversity, as complementary papers in this special issue of *Advances in Speech-Language Pathology* were to emphasize different aspects of Jarrod's linguistic and nonlinguistic development in recommendation of a clinical plan. By report, the child scored within expected limits on tests of hearing, nonverbal intelligence, and receptive and expressive language. There were, however, indications that the child presented with Attention Deficit Hyperactivity Disorder (ADHD), being medicated with Ritalin, and evidenced fine motor difficulties. Case history by parent report was unremarkable. With respect to the phonological system, samples collected from the child were extensive and tapped a wide range of the child's phonological abilities in perception, production, metalinguistic and phonological awareness. Nonetheless, as with any testing situation, there are limitations of the data. Limitations may be due to, for example, the internal validity of a test itself, procedural reliability of test administration, inter- and intrajudge reliability of phonetic transcriptions and scoring, and missing or uninterpretable data and recordings. In Jarrod's case, there is a further drawback because any of the clinical interpretations offered in this compendium are in the absence of having observed or interacted with the child. The end recommendations can only be taken as in principle illustrations. Given these bounds, and erring on the side of caution, our goal is to provide a tutorial on the selection of treatment targets based on phonological complexity, with a limit to the discussion of complexity associated specifically with syllables. This is not meant to say that other aspects of Jarrod's linguistic or nonlinguistic development do not also warrant clinical attention. By the collection of papers in this issue, it is clear that Jarrod's phonological system was lagging in multiple ways, and that other aspects of the phonology were viable targets for intervention. This notwithstanding, the emphasis on complexity within the context of syllables may not be out of line in Jarrod's case because complex input appears to benefit a wide range of speech and language disorders cross-cutting varied clinical populations (e.g. Thompson et al., 2003). Our specific interest in syllables complements

other available tutorials on complexity that derive from markedness, developmental norms, stimulability, consistency, and minimal pairs (Barlow & Gierut, 2002; Gierut, 2001; 2004; in press; Gierut, Morrisette, Hughes, & Rowland, 1996). This thereby allows for an integration of syllabic, segmental and developmental considerations in the identification of complex treatment targets across published manuscripts. We begin with an overview of the principles of complexity that affect the syllable structure of language generally, with an emphasis on the onset clusters of English. The body of the paper introduces guidelines to syllable analyses that lead to the selection of a complex onset cluster for treatment. We then implement these procedures in analysis of Jarrod's cluster data. The resulting prediction is that treatment based on syllable complexity leads to expansive generalization learning of both clusters and singletons.

Complexity and markedness: The phonetic inventory

One type of phonological complexity is "functional" in nature, as defined by language laws (Gierut, in press; Rescher, 1998). Language laws are universal tendencies governing the relative sound co-occurrences that hold within and across languages (Coetzee, 2002). Laws have materialized from examinations of the phonological systems of fully developed languages (Greenberg, 1978; Ladefoged & Maddieson, 1996), but are equally successful in characterizing developing, atypical, or second language sound systems (e.g. Dinnsen, Chin, Elbert, & Powell, 1990; Eckman & Iverson, 1993; Jakobson, 1941/1968). Language laws work in a predictable way such that they may be used clinically. In general, language laws state that a complex structure of grammar implies (or predicts) a related co-occurring simpler structure. Within the linguistics literature, the complex structure is denoted as property X and termed *marked*, whereas simpler structure is labelled as Y and termed *unmarked*. For our purposes, we use the terms "complex" and "simple" throughout for ease of explication. Formally, language laws are captured by the following statement: the presence of a more complex linguistic property X implies the presence of a related simpler property Y, but not vice versa. Notice that there is a unidirectional relationship where X predicts Y, but not the reverse. Given the implicational relationship between these properties, three possible (i.e. child) grammars are predicted: (1) a grammar may contain neither complex X nor simple Y; (2) a grammar may include both complex X and simple Y; or (3) a grammar may include only the simple property Y, but not the complex X. Language laws exclude a fourth possible grammar that consists of a more complex property X in the absence of the simpler Y. If this occurs, it is a seeming violation of the law because the complex always implies the simple given the unidirectional nature of co-occurrences. In fully

developed languages, the seeming violations have been addressed through statistical analyses (Coetzee, 2002). For clinical cases, seeming violations may be traced to the richness and timing of the speech sample (Gierut, in press). All in all, the consequence for phonological treatment is that a complex target predictably leads to acquisition of related simpler targets without direct intervention. The applied consequences thus have potential to improve the efficacy of clinical treatment.

Lawful relationships in grammar can be illustrated by considering a few observed co-occurrences involving the classes of stops, fricatives, affricates, and onset clusters (Greenberg, 1978; Ladefoged & Maddieson, 1996). One language law states that the presence of fricatives in a sound system implies the presence of stops, but not vice versa. The result is that a child's inventory may consist of neither fricatives nor stops, both fricatives and stops, or stops only; but an inventory is not expected to have fricatives alone to the exclusion of stops. Two other laws that are relevant to the subsequent discussion are that affricates imply fricatives, and that onset consonant clusters imply singletons, most notably the affricates. Importantly, these co-occurrence relationships associated with stops, fricatives, affricates and onset clusters have been borne out in typical and atypical phonological development (Dinnsen & Elbert, 1984; Elbert, Dinnsen, & Powell, 1984; Elbert & McReynolds, 1979; Gallagher & Shriner, 1975; Gierut & O'Connor, 2002; Ingram, Christensen, Veach, & Webster, 1980; Lleó & Prinz, 1996; 1997; Schmidt & Meyers, 1995). These laws are also consistent with principles of learnability in advocating complexity as the trigger of acquisition. The evidence that supports the clinical applicability comes from experimental studies of treatment efficacy (see Gierut, 2001; 2004, for review). The basic experimental approach has been to teach one group of children a complex phonological target in treatment and another group, the complementary simple target. Across studies, a converging result has been that treatment of the complex property results in children's generalization to both the complex and simpler aspects of the law. Treatment of the complex thus promoted children's learning of complex plus simple structure. The same did not occur among the comparison groups being taught simpler treatment targets. Treatment of simple targets results in limited generalization to those targets that were the focus of intervention; other complex properties of the sound system did not generally improve. Here, treatment of a simpler property triggered learning in that property alone.

One additional point worth mentioning is the potential for these three language laws to engage in a chained relationship: clusters imply affricates, affricates imply fricatives, and fricatives imply stops. One hypothesis is that treatment of onset clusters will enhance a child's learning of affricates and in turn,

the learning of affricates will enhance learning of fricatives and consequently, learning of fricatives will enhance learning of stops (Gierut, 1999; Gierut & Champion, 2001; Gierut & O'Connor, 2002). Following from the chain, it is possible to promote broad system-wide generalization by targeting onset clusters in treatment. This recommendation follows from the lawful predictions, is consistent with models of language learnability, and of most importance, addresses an area of the phonology (i.e. clusters) that is known to be problematic for children with phonological disorders (Smit, 1993). Moreover, from the predicted course of learning, the recommendation hones in on other apparent errors in children's repertoires. Children with disorders often have errors associated with fricatives, affricates, and velar stops as characterized by the prevalent use of stopping, deaffrication, and fronting processes, respectively (Ingram, 1989; Lowe, 1994). Thus, given the potential benefits that may be afforded by treatment of onset clusters, a first step of this tutorial involves describing a child's phonetic inventory, as outlined in (1) below. Following established procedures (Stoel-Gammon, 1985), the phonetic inventory includes all singleton sounds that a child produces with a two time minimum occurrence. The child's productions are examined independent of the intended target sound and independent of context. Thus adult-like and non-adult-like sounds are entered into a child's inventory regardless of where they occur in a word.

(1) Guidelines for determining a child's phonetic inventory

Identify all singletons produced with a two time minimum occurrence, independent of target sound and word position. Include adult-like and non-adult-like phones in the inventory. Use the inventory to structure the probe of generalization learning.

Once the singleton inventory is in place, it is then possible to determine which sounds remain to be learned by the child. These sounds will not be taught given the focus on clusters; instead, gaps in the child's inventory will be used to monitor generalization learning. Keep in mind that singletons are not the goal of treatment herein, but nevertheless, improvements in singletons (especially the stops, fricatives and/or affricates) are expected given the lawful co-occurrences. Consequently, gaps in a child's singleton inventory inform generalization learning, and should be sampled on probe measures.

Complexity and clusters: Sonority difference and minimal distance

Consonant clusters are governed by language laws associated with the structure of the syllable. A syllable may be composed of three parts: the onset, nucleus or vowel, and coda (Blevins, 1995). The vowel

Table I. Sonority differences for target English onset clusters.

Target English onset clusters	Sonority difference
/tw- kw-/	6
/pl- kl- pr- tr- kr-/	5
/bl- gl- br- dr- gr- sw-/	4
/fl- sl- fr- θr- ʃr- /	3
/sm- sn-/	2
/sp- st- sk-/	-2 (adjuncts)
/spl- spr- str- skr- skw-/	3-element clusters

- b. Compute the sonority difference of each cluster produced using Table I and Figure 1 as references. Credit the child with a given sonority value if there are two occurrences of a cluster with that value (e.g. A child who produces [tw-] once and [pw-] once would be credited with the sonority difference of 6 for the voiceless stop + glide combination. A child who produces [tw-] twice would likewise be credited with the sonority difference of 6.)
- c. Examine the sonority differences and determine which is smallest as the child's minimal distance.

This alternate characterization of clusters based on sonority difference and minimal distance has been used with success in describing children's production of and errors in cluster use (Barlow, 2001; 2004; Gierut, 1999; Pater & Barlow, 2003), but a few additional points about the procedures are worth mentioning. First, it must be recognized that the ultimate target selection must be weighed relative to the child's overall phonological status. For example, if a child demonstrates knowledge of all target sonority differences and accurately produces clusters, then treatment of clusters would not be an appropriate treatment target.

Second, the clusters shown in reference Table I are limited to the adult target, but the analysis does provide for non-adult-like consonant sequences. It is not only possible, but likely that a child will produce clusters that do not occur in English. These clusters are still "legal" if they accord with the SSP. A common example is children's production of the voiced stop + glide sequence [bw-], which is often a substitute for targets /bl- br-/ (Greenlee, 1974). [bw-] has a sonority difference of 5 because it involves a voiced stop (6) followed by a glide (1), following from Figure 1. Even though [bw-] is not a cluster of English, a sonority difference of 5 is permissible in English, e.g. /pl- kl- pr- tr- kr-/. In this example, the child's use of [bw-] is non-adult-like in segmental composition, but adult-like in its organization as a well formed onset of a syllable.

A third point of mention is that the classification of a child's clusters based on sonority is different from traditional codings of clusters. Consider the sequences /pl- bl- fl-/. Historically (e.g. Smit, 1993), these would be called "l-clusters". Under a traditional

classification, treatment of one l-cluster would give rise to examining change in other l-clusters (Powell & Elbert, 1984). However, under the coding of sonority, /pl- bl- fl-/ would not be equivalent because they range in complexity from sonority differences 5 to 4 to 3, respectively (cf. alternate views as summarized in Gierut, 1999). These clusters actually come from distinct linguistic categories, which has potential ramifications for generalization learning. Remember that treatment of clusters with a small sonority difference is said to promote generalization to clusters of all greater differences. In our example then, /fl-/ emerges as an optimal candidate for treatment given its smaller sonority value. If /pl- bl-/ were selected instead, they would not be expected to promote change across the l-cluster category. While provocative, it is important to ask whether these effects are actually borne out in clinical applications. To address this question, we must consider the potential caveats in the classification of clusters.

Caveats to complexity: Adjuncts and 3-element clusters

Three classes of clusters stand out with respect to the organization of syllables. These are the 2-element sequences /sp- st- sk-/, the related clusters /sm- sn-/, and the 3-element clusters /spl- spr- str- skr- skw-/. Two-element s-clusters are peculiar because they violate the SSP given that a more sonorous fricative /s/ precedes a less sonorous stop /p t k/ (Figure 1). The SSP states that the sequence should be the reverse, ordering from low to high sonority. In fully developed and developing phonological systems, /sp- st- sk-/ often have a distinct pattern of occurrence (Barlow, 2001, for review). In developing systems too /sp- st- sk-/ are different in that they have a sonority difference value of -2. The negative sonority value implies that /sp- st- sk-/ are the most complex clusters of all, but normative data show in fact that these are among the first acquired (Smit, Hand, Freilinger, Bernthal, & Bird, 1990; Smit, 1993). The uniqueness of /sp- st- sk-/ has a linguistic explanation that posits the fricative /s/ as an "add-on" or adjunct to the syllable. In other words, /s/ is not thought of as part of a cluster (for a more detailed explanation, see Clements, 1990). To express this, /sp- st- sk-/ are conventionally called *adjuncts* within the linguistics literature, whereas all other clusters are termed *true clusters*. Such terminological distinctions may be necessary for linguistic theory, but the real clinical question is how treatment of /sp- st- sk-/ affects children's generalization learning. For this, we consult a clinical comparison of treatment of true versus adjunct clusters (Gierut, 1999).

In this study, children with phonological disorders were taught either a true or an adjunct cluster, and the cluster treated involved either a small or greater sonority difference. Treatment of clusters thus served as the independent variable, whereas accuracy

of untreated clusters was measured as the dependent variable. Three main findings emerged. First, treatment of true clusters promoted greater generalization than did treatment of /sp- st- sk-/. Second, in treatment of true clusters, a small sonority difference triggered greater learning than a greater difference. Third, the learning patterns varied by treatment group. Those who were taught an adjunct had spotty learning as compared to a linear progression of generalization for the children treated on true clusters. In all, the learning data suggested that /sp- st- sk-/ were less than ideal candidates for treatment, and that true clusters with a small sonority difference were the more efficacious targets. From Table I and Figure 1, the true clusters that best meet this description are /sm- sn-/, which brings us to a second caveat of complexity in clusters.

The clusters /sm- sn-/ walk a fine line between true and adjunct status. On the one hand, they accord with the SSP by organizing from low to high sonority. On the other hand, they are comprised of an s + stop (albeit nasal) sequence as in the case of the adjuncts. For languages of the world, this has resulted in some indeterminacy. Some languages (e.g. Italian) mix /sm- sn-/ with the adjuncts; but other languages (e.g. English; cf. Barlow, 2001, for review) integrate /sm- sn-/ with the true clusters. The same kind of indeterminacy has been observed in children's phonologies (Barlow, 2001): some children put /sm- sn-/ in the category of adjuncts and others, in the category of true clusters. This has important clinical consequences for generalization learning. If a child groups /sm- sn-/ with the adjuncts, then treatment of /sm- sn-/ is expected to result in limited learning. This follows from the aforementioned treatment results where children who were taught an adjunct exhibited spotty performance. But if a child groups /sm- sn-/ with true clusters, then treatment of /sm- sn-/ will lead to the greatest learning of all cluster types. The reason is that /sm- sn-/ have the smallest minimal distance as most complex. Thus, treatment could have opposite effects depending on a child's conceptualization of /sm- sn-/. For this reason, it is necessary to determine the patterning of /sm- sn-/ relative to the adjuncts by examining a child's substitutions, as a guideline of cluster analysis.

(3) Guidelines for identifying 2-element clusters as targets for treatment

- a. Identify all target clusters that have a smaller sonority value than the child's entry minimal distance. These constitute the pool of possible clusters for treatment.
- b. Set aside /sp- st- sk-/ as treatment targets.
- c. If /sm- sn-/ are in the pool, list the child's substitutions for these targets. Compare the /sm- sn-/ substitutes to the substitutes for /sp- st- sk-/. Repeat the comparison for other true

clusters. If the substitutes for /sm- sn-/ overlap with those used for /sp- st- sk-/, then set aside /sm- sn-/ as possible treatment targets. If the substitutes for /sm- sn-/ are similar to the true clusters, keep /sm- sn-/ in the treatment target pool.

Before going on to select the specific 2-element consonant cluster for treatment, it is necessary to entertain one final possibility in cluster treatment, that being a 3-element sequence. Three-element clusters also pose a caveat to complexity because they resemble both an adjunct and a true cluster at the same time. Like an adjunct, they consist of an s + stop sequence; but like a true cluster, they consist of a sequence that matches the SSP. To illustrate, consider /spl-/. For this cluster, the more sonorous fricative /s/ is followed by the less sonorous stop /p/ consistent with an adjunct; but continuing, the less sonorous stop /p/ is followed by the more sonorous liquid /l/, consistent with a true cluster. How then does a 3-element cluster influence treatment? Does it hinder learning like an adjunct or facilitate learning like a true cluster?

In a clinical treatment study of 3-element clusters, each type of learning was observed (Gierut & Champion, 2001). Some children showed minimal gains in treatment, whereas others showed widespread change that extended to the singletons, most notably the affricates. Of significance, it was possible to predict which pattern of generalization a child would exhibit in treatment of 3-element clusters, based on his or her knowledge of singleton phonemes. The notation $C_1 C_2$ and C_3 will be used to reflect each consonant of the 3-element cluster, i.e. $C_1 C_2 C_3$. Results showed that when C_1 and C_2 were phonemic for a child, generalization learning was minimal after treatment of a 3-element cluster. Presumably, these children parsed the treated 3-element cluster with emphasis on the first two sounds of the sequence. This highlighted the adjunct portion of the cluster (e.g. /sp-/ in /spl-/) and as a result, generalization learning was inhibited. When C_2 and C_3 were phonemic instead, then generalization was expansive. Here, children apparently parsed the treated 3-element cluster with emphasis on the second and third sounds of the sequence, thus spotlighting the true portion of the cluster (e.g. /pl-/ in /spl-/). From these results, it appears that complex 3-element sequences have the potential to guide children on one of two paths of learning. Moreover, the path a child takes seems to be influenced by their phonemic inventory, such that phonemic knowledge of $C_2 C_3$ is most effective and $C_1 C_2$, least effective. In addition to these options, a child may exhibit other combinations of singletons as subsets of the 3-element cluster. For example, a child may use C_1 phonemically, but not C_2 or C_3 . The full range of phonemic permutations was not represented in the study population, and so continued research is

needed to determine the effects generalization learning when just one member of the 3-element cluster is included in the phonemic repertoire but not others. Until those data become available, it is only possible to speculate about the facilitating effects of C_1C_2 in 3-element cluster treatment. This is reflected in the next set of guidelines for cluster analysis.

(4) *Guidelines for evaluating 3-element clusters as possible targets for treatment*

- a. Determine the phonemic status of C_1 /s/, C_2 /p t k/, and C_3 /l r w/. Do this by finding minimal pairs associated with these segments in the child's phonological sample.
- b. If the child uses only C_1 , but not C_2 or C_3 (alternatively C_2 but $*C_1C_3$ or C_3 but $*C_1C_2$), then return to the guidelines in (3) for cluster selection. Choose a 2-element cluster for treatment with the smallest sonority difference relative to the child's minimal distance.
- c. If C_1 and C_2 are phonemes for the child and C_3 is not, set aside 3-element clusters as possible targets for treatment. Return to (3) to choose an optimal 2-element cluster for treatment.
- d. If C_2 and C_3 are phonemes and C_1 is not, choose 3-element clusters as the optimal (most complex) target of treatment. Set aside 2-element clusters as targets for treatment, but monitor these for generalization learning.

Applications of complexity in the case of Jarrod

In the final section of this paper, we put together the guidelines of cluster analysis in selection of a target onset cluster for treatment. Keep in mind that the analysis derives from lawful relationships of language that bear on the occurrence of clusters and singletons, including 2- and 3-element sequences, adjuncts, affricates, fricatives and stops. By emphasizing a complex target cluster in the selection process, the steps of analysis will lead to recommendations about complex treatment targets, thereby bridging clinical practice with formal theories of language learnability in crafting an efficacious teaching plan.

Phonological sample. The data used in our analysis came from the *Diagnostic Evaluation of Articulation and Phonology* (DEAP; Dodd, Hua, Crosbie, Holm, & Ozanne, 2002). This was supplemented by 90 additional words that we submitted, drawn from the *Phonological Knowledge Protocol* (PKP, Gierut, Elbert, & Dinnsen, 1987) and *Onset Cluster Probe* (OCP, Gierut, 1998a). When combined with the DEAP, the supplemental items yielded a complete representative sample of all target phonemes and onset clusters of English in all relevant word positions and in multiple exemplars.

The supplemental words were elicited using a spontaneous picture-naming task, and we asked that the elicitation procedures be consistent with the sampling methods described by Gierut (1998a). The sampling procedures typically involve a first attempt to elicit the words using a question or close sentence prompt (e.g. "What colour is this?" or "The ball isn't red, it's ____"). If the child fails to produce the word spontaneously, the word is cued in delayed imitation (e.g. "It's a blue ball. What is it?"). Direct imitation is used only as a last resort (e.g. "Say blue"). We assume the data were collected in this manner, being audio- and video-recorded. The data were phonetically transcribed using narrow notation of the IPA by a trained listener who was familiar with the Australian dialect of English (provided in Holm, 2005). There were no estimates of inter- or intrajudge phonetic transcription reliability provided in the data set; nor was procedural reliability of probe/test administration available for these samples. Under ideal circumstances, reliability is computed by appealing to articulatory, acoustic, and videotaped data in establishing intra- and/or interjudge estimates. The validity of these estimates will of course vary with the quality of the recordings, training in the dialect of the speaker, and the amount of background interference, which to our knowledge were not controlled for in the collection and dissemination of these data. This notwithstanding, the transcriptions that were provided were taken as the source for our illustration of the analysis of clusters.

Jarrod's phonetic inventory. Jarrod produced the following singletons with at least a two time occurrence [m n ŋ p b t d k g ʔ f θ ð s ʃ l r ɹ w j h]. Notice that the child's singleton repertoire included nasals, stops, fricatives, liquids and glides, and the phones produced were consistent with English. Jarrod's phonetic inventory also included two non-ambient phones, namely the velar fricative [x] and the lateral fricative [ɬ]. From the phonetic inventory, we identified gaps in the child's repertoire. For Jarrod, the phonetic exclusions included fricatives [v z] and affricates [tʃ dʒ]. These are sounds that are to be monitored during the course of cluster treatment. Predictably, treatment of a cluster should promote generalization to singletons, most notably, the affricates. The affricates in turn are predicted to affect the child's production of fricatives.

Jarrod's sonority differences and minimal distance. Jarrod's data were organized by target cluster and sonority difference as illustrated in the appendix for a subset of the data. For the most part, Jarrod reduced consonant clusters to singletons (e.g. [ni] for *sneeze*); however, he did evidence some rudimentary knowledge of clusters. In particular, Jarrod produced the target English clusters [br-] and [gr-] each a minimum of two times. The cluster [gr-] occurred once in the word *grow* (correct) and again as a

substitute in the word *quack* (incorrect). Likewise, the cluster [br-] was used in the words *brown* (correct) and *blow* (incorrect). Note that segmental accuracy was not a requirement in the analysis; rather we are trying to establish which sonority differences Jarrod allows in the phonology. By using Table I and Figure 1 as references, it can be seen that a voiced stop+liquid sequence as in the child's production of [br- gr-] has a sonority difference of 4. Because there were at least two instantiations of this sonority difference value, Jarrod was credited with knowledge of sonority difference 4.

Another cluster that Jarrod produced on at least two occasions was [bw-], e.g. *present* and *front*. Remember that the analysis of clusters is independent of target English, so non-adult-like clusters like this should be considered. While [bw-] does not occur in English, it does conform to the SSP given that the voiced stop is less sonorous (6) than the following the glide (1) on the sonority hierarchy in Figure 1. The sonority difference for [bw-] is 5, for which Jarrod also received credit.

Lastly, in accord with the guidelines in (2b), Jarrod was credited with the sonority difference 6 because he produced [pw-] and [kw-] one time each for the target words *shoe* and *squeak* respectively. Both of these clusters consist of a voiceless stop (7) followed by a glide (1), resulting in a sonority difference of 6.

A few other clusters were incidentally produced by Jarrod, but these were not credited because they did not meet the criterion of a two time occurrence of a specific sonority difference. In all, Jarrod evidenced knowledge of sonority differences 6, 5 and 4, with 4 being the minimal distance allowed in the child's grammar.

Jarrod's use of adjuncts. Based on complexity, the recommendation for treatment is to select a cluster with smaller minimal distance than the child's presenting system. Given Jarrod's minimal distance of 4, clusters with a sonority difference of 3, 2 or –2 are all smaller in value as possible treatment options. We outright eliminated the –2 set /sp- st- sk-/ given their adjunct status and limiting effects on generalization. Sonority differences 3 and 2 remained as treatment options. Clusters with a sonority difference of 2, i.e. /sm- sn-/ are preferred because they are the most complex 2-element sequences. But because of their indeterminacy, we first examined Jarrod's substitutions, comparing /sm- sn-/ to /sp- st- sk-/ and to the other true clusters.

Data in the appendix show that Jarrod's typical production of /sm- sn-/ was a nasal, e.g. [meou?] for *smell* and [ni] for *sneeze*. Jarrod reduced clusters with a sonority difference of 2 to the second consonant of the sequence. When we looked at Jarrod's substitutes for adjuncts /sp- st- sk-/, there was the same reduction pattern. For example, *spider* was realized as [bɑɪd], *star* as [dɑ], and *school* as [gʊ]. For the adjuncts, Jarrod used the second consonant of the

sequence as the substitute, which suggested that Jarrod merged the true cluster category /sm- sn-/ with the adjuncts /sp- st- sk-/. For this reason, we hypothesized that /sm- sn-/ might not ultimately be an appropriate treatment option. For a definitive decision, we had to compare the substitutions for /sm- sn-/ to the other true clusters. The data again showed that Jarrod reduced true clusters to the second member of the sequence, either [r ɹ] or a glide. This can be seen in Jarrod's production of *train* as [jeɪn] or *glasses* as [jʌθe] in the appendix. Taken together, the data showed that Jarrod's pattern was to reduce clusters to the second member of the sequence, regardless of whether the target cluster was /sm- sn-/, an adjunct, or a true cluster. Thus, the predicted generalization to follow treatment of /sm- sn-/ could not be determined a priori from the available data. If we were to treat a 2-element cluster in this case, we would err on the side of caution by considering only clusters with a sonority difference of 3 as potential targets. These are the voiceless fricative+liquid clusters /fl- sl- fr- θr- ʃr-/. To complete the guidelines for cluster selection though, we entertained one last teaching option, that being 3-element clusters.

Jarrod's use of 3-element clusters. Recall that a key piece of evidence in determining whether treatment of 3-element clusters is appropriate is the child's phonemic inventory. We therefore examined whether Jarrod's phonemic inventory contained C₁ /s/, C₂ /p t k/, or C₃ /l r w/; these are the subset of sounds that comprise the target 3-element clusters of English. Following the literature, Jarrod's phonemic use of these sounds was determined through minimal pairs (Gierut, Simmerman, & Neumann, 1994). Jarrod did not produce any minimal pairs involving C₁ /s/. He did, however, produce minimal pairs associated with C₂, namely /p/, and C₃, specifically /r w/. Examples included the minimal pairs [p^ha] *car*–[ba] *bath*, where /p b/ are contrastive. He also produced minimal pairs [jeɪn] *train*–[beɪn] *van* (i.e. /ɹ b/ as contrastive) and [wou] *blue*–[nou] *nose* (i.e. /w n/ as contrastive). Jarrod's phonemic inventory thus included C₂ and C₃, but not C₁; this is the ideal inventory composition for treatment of a 3-element cluster. Thus, the 2-element clusters were set aside as treatment options, and the 3-element cluster emerged as an optimal (complex) target. The specific cluster /spr-/ is an appropriate choice since /p/ and /r/ were phonemic for Jarrod.

A number of predictions about generalization learning follow from selection of this target. One prediction is that treatment of /spr-/ will result in widespread gains to Jarrod's production of untreated 2-element true clusters. Gains are expected in all the sonority difference values shown in Table 1 (i.e. 6, 5, 4, 3, 2). Treatment of /spr-/ will also prompt change in untreated singletons. This follows from the chaining of language laws, such that clusters imply

affricates, affricates imply fricatives, and fricatives imply stops. Because Jarrod had gaps in his phonetic inventory restricting the use of [v z] and [tʃ dʒ], these too are expected to improve. The extensive generalization that is predicted thereby supports the treatment of the 3-element cluster /spr-/ as both a complex and an efficacious target for this child.

Final remarks

While the focus of this tutorial has been on the selection of complex targets for treatment, the importance of the method of treatment and measurement of generalization should not be ignored. With respect to methods of teaching, the practicing clinician has a range of options available, with no one approach having yet been demonstrated as more efficacious than others (Gierut, 1998b). From a research perspective, it is imperative that structured teaching procedures be employed for purposes of reliability and validity of the experimental effects. The structured teaching procedures we use in the laboratory have been described in detail elsewhere (Gierut, 2005), and include but are not limited to the use of successive phases of instruction, auditory and visual feedback, corrective modelling, visual stimuli, successive approximations, and so forth. Inherent to any teaching program albeit in the lab or clinic is the ongoing re-evaluation of goals and strategies of elicitation and correction as based on a child's day-to-day learning.

With respect to generalization, one of the advantages of a learnability approach to treatment is that testable hypotheses about phonological change emerge as a result of target selection. Treatment and monitoring become practical ways to test these hypotheses. In the case of Jarrod, it is important to monitor several aspects of the child's phonology using probe measures. Probes should be designed to sample the 3-element clusters /spl- spr- str- skr- skw-/. We should also sample the 2-element true clusters of all sonority differences as in Table I. The singleton fricatives and affricates must be probed given the gaps in the child's phonetic inventory. Finally, we should track production of the adjuncts /sp- st- sk-/ to determine change, albeit positive or negative. Under ideal circumstances, probe measures should be administered regularly throughout the course of intervention, but are essential prior to and immediately following treatment. Results from the probes will confirm (or refute) the predictions that follow from learnability theory, such that Jarrod's post-treatment generalization learning will serve as the basis for subsequent goal selection. Goal selection in successive rounds of treatment would revisit principles of learnability, emphasizing complexity of the input (e.g. Gierut, 2001). The success of treatment is of course expected, but there have been reported cases where learning lags despite the best efforts (Dinnsen & Gierut, to appear). For example,

some common error patterns that are known to be particularly resistant to change include cases of complementary distribution, interacting error patterns, chain shifts, and errors that derive from opacities associated with feeding or bleeding rule orders. In keeping with the linguistic theme, it should be noted that these same sorts of output patterns occur in fully developed languages and, as with such clinical cases, pose particular theoretical challenges.

In conclusion, we have applied principles of complexity to illustrate target sound selection for the case of Jarrod, with emphasis on consonant clusters in treatment of /spr-/. The target goal that emerged from this analysis of clusters is consistent with the lawfulness of language, the basic premises of learnability theory, and demonstrations of treatment efficacy that support evidence-based practice. Treatment of clusters is just one consideration in the application of phonological complexity and it should be balanced against, and incorporated with others for a multidimensional approach to phonological remediation. Developmental, segmental, syllabic, methodological, and lexical variables associated with phonological complexity should all be weighed in tandem. With continued clinical research, there is no doubt that other added properties of complexity will emerge as applicable to child phonology and the intervention process. This will aid in our understanding of phonological treatment and the enhancement of treatment efficacy, but it will also inform formal theories of phonology and language learnability.

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Appendix A

This appendix shows examples of the transcribed data that were analysed for this tutorial. The transcriptions were provided by Holm (2005). Diacritics were removed where needed for simplicity of illustration (e.g. tone). Jarrod was credited with the production of a rhotic liquid for the transcriptions of both [r] and [ɹ] (McLeod personal communication).

Sonority Difference	Target Cluster	Orthography	Transcription of target word (Holm, 2005)	Transcription of Jarrod's production (Holm, 2005)
6	/tw-/	twelve	twelv	dwæɹ̥
		twins	twɪnz	wēn:
		twist	twɪst	wεθ
	/kw-/	quack	kwæk	gɹæ̃ ^h
		queen	kwin	wēɪn
		quiet	kwaɪət	raɪd̥e
5	/pl-/	(aero)plane	erəpleɪn	ʔɪdəweɪn
		plate	pleɪt	reɪʔ
		play	pleɪ	ɹæɪ:
	/kl-/	clock	kɒk	j:ɹʔ
		cloud	klaʊd	jaude
		clown	klaʊn	jæʊ
5	/pr-/	prize	praɪz	wɑɪ
		present	prezənt	bweθdēn
		pretty	prɪti	jeʔdɪ
	/tr-/	train	treɪn	ɹeɪn
		(a) tree	tri	dɪmwəɪ
		truck	trʌk	wɹʔ
/kr-/	crab	kræb	bɹwɑ ~ wæʔh	
	crawl	krɔl	u:wɔɹ	
	cry	kraɪ	wɑɪ	
4	/bl-/	black	blæk	bwæʔ
		blow	blou	bɹou
		blue	blu	wou
	/gl-/	glasses	glazəz	jɹʔθe
		glove	glʌv	jɹʌ
		glue	glu	ɹəʊ
/br-/	bread	bred	ɹeɪ	
	brown	braʊn	bɹaʊn	
	(you) brush	jubrʌʃ	ɹmwɹʌʃ	

(continued)

Appendix A. (Continued).

Sonority Difference	Target Cluster	Orthography	Transcription of target word (Holm, 2005)	Transcription of Jarrod's production (Holm, 2005)	
3	/dr-/	dress	dres	ɹe	
		drive (it)	draiv	m ^b waiɹeɹ̃	
		drum	drʌm	bəwʌn	
	/gr-/	grass	gras	ʊwə	
		green	ɡɹin	ɡɹiɹ̃ ~ ɡɹiɹ̃ ~ ʊwɛn	
		grow	ɡrou	ɡɹʌɹ̃	
	/sw-/	sweep	swip	w:i	
		swim	swim	wɛn	
		swing	swiŋ	ɹɛŋ	
	3	/fl-/	(the) flag	flæg	dəwə
			flower	flaʊə	bwaʊ
			fly (it)	flaɪt	bwaɪʊt̃
		/sl-/	sleep	slip	wəiɹ̃
			slide	slaɪd	ɡɹiːaɪ:
			sleeve	sliv	j:əi
/fr-/		frog	fɹɔɡ	wɹɔ	
		front	fɹʌnt	bwʌn	
		fruit	fɹut	ɹəʊ	
/θr-/		thread	θred	ʊəɹ̃	
		three	θri	ɹəi	
		throw (it)	θrou	fɹouɛɹ̃t̃	
/ʃr-/		shred	ʃred	ʊwɛd̃	
		shrink	ʃɹɪŋk	ʊɹiŋ	
		(a) shrub	ʃɹʌb	bəʊwʌ:	
2	/sm-/	smell	smel	mæʊ	
		smile/hug	smɑɪl hʌɡ	maɪtʃʊ	
		smoke	smouk	m:ouɹ̃	
	/sn-/	snail	sneɪl	lənɛɪdɹ̃	
		snake	sneɪk	fneɪɹ̃ ~ meɪɹ̃	
		sneeze	sniz	ni	
-2 (adjuncts)	/sp-/	spider	spaɪdə	baɪdʌ	
		spill (the drink)	spɪl	bɪʊdəwəiɹ̃	
		spoon	spun	bū	
	/st-/	star	sta	də	
		stop	stɒp	dɒɹ̃k ^h	
		stove	stouv	dou	
/sk-/	(um a) scarf	skaf	əndʌddə		
	school	skul	ɡɹʊ		
	skate	skeɪt	steɪɹ̃		
3-element	/spl-/	splash	splæʃ	wʌʃ	
		splashing	splæʃɪŋ	wæɹ̃hɹ̃dɪŋ	
		splitting	splɪtɪŋ	wɛɹ̃dɪŋ	
	/spr-/	spray(ing)	spreɪ	wɛɹ̃t̃hɪ	
		spread (it)	spreɪd	wɛɹ̃ɹ̃e	
		spring	sprɪŋ	wɹiŋ	

(continued)

Appendix A. (Continued).

Sonority Difference	Target Cluster	Orthography	Transcription of target word (Holm, 2005)	Transcription of Jarrod's production (Holm, 2005)
		strawberry	strɔ̃bri	sjouwɨ
	/str-/	street	strit	uwɨ
		stripe(s)	straɪp	uwɑɪ
		scream	skrim	wəɪn
	/skr-/	scratch	skrætʃ	u::wæ
		scrub	skrʌb	u::wʌʔ
		square	skweə	jeə
	/skw-/	squeak	skwik	kwik ¹
		squirrel	skwɪrəl	wɪdu