Interactivity Between Phonological Levels in Speech Output: Example From a Child With 3-Methylglutaconic Aciduria Type I

Interactivité entre les niveaux phonologiques dans la production de la parole : exemple d'un enfant atteint d'acidurie 3-méthylglutaconique de type I

KEY WORDS

3-METHYLGLUTACONIC ACIDURIA TYPE I

MULTISYLLABIC WORDS

NONLINEAR PHONOLOGY

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Abstract

Speech production is the result of a complex set of interactions between components of the language processing system. The longer the word, the greater the possibility for 'error,' because of interactions between word length, stress, CV sequences, consonants and vowels. Nonlinear phonological frameworks influenced by Optimality Theory and connectionist frameworks allow description of output at various levels of the phonological system and their interactions, and thus can help with interpretation of variable speech production patterns. The current paper provides a nonlinear analysis of one 8-year-old's speech profile, which shows interactions between word structure and segments as word complexity increases. The participant has a rare metabolic condition: 3-methylglutaconic aciduria type I. To date, no reports have described speech profiles of children with this condition and thus, the paper also contributes to the literature on that condition.

Abrégé

La production de la parole est le résultat d'un ensemble complexe d'interactions entre les composantes du système de traitement du langage. Plus le mot est long, plus grande est la possibilité d'une « erreur » à cause des interactions entre la longueur du mot, l'accentuation, les séquences CV, les consonnes et les voyelles. Des cadres non linéaires de la phonologie influencés par la théorie de l'optimalité et des cadres connexionnistes permettent la description de la production à divers niveaux du système phonologique et de leurs interactions, et peuvent ainsi contribuer à l'interprétation des schémas variables de production de la parole. Le présent article offre une analyse non linéaire du profil de parole d'un enfant de huit ans, qui montre les interactions entre la structure d'un mot et ses segments à mesure que la complexité du mot augmente. Le participant a une condition métabolique rare d'acidurie 3-méthylglutaconique de type I. Jusqu'à maintenant, aucun rapport n'avait décrit les profils de parole d'enfants ayant cette condition et, ainsi, l'article contribue à enrichir les connaissances portant sur cette condition.

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Phonological development requires learning not only the speech sounds of an ambient language, but also their context of occurrence, both phonologically and in relation to the lexicon, morphology, and syntax. Phonological contexts include for example, word length, word or phrasal stress, position in the word or segmental (phoneme) sequences. Development necessarily requires flexibility within and across the various components of a given system. One consequence of flexibility is variable output (production) during periods of developmental change in the phonological system (Becker & Tessier, 2011). Words, segments, or word structures may show variability as the element in question moves from absence to emergence to mastery. For example, for one typically developing child, Stemberger (1988) observed context-dependent variability in production of voiced stop codas (syllable-final consonants). Generally, voiced stop codas deleted. However, if the word following the voiced stop coda started with a vowel, the voiced stop appeared, syllabified as onset to the vowel-initial word. Other linguistic and non-linguistic factors may result in variability. For example, lexical input frequency may affect relative accuracy of phonological form: in Ota and Green's analysis of corpora from three children (2013), word-initial cluster accuracy was higher in more frequently heard words. Sosa and Stoel-Gammon (2012) noted higher variability in low frequency words in early word acquisition (although not higher accuracy) and higher accuracy and lower variability in words with dense phonological neighbourhoods (many similar forms) versus sparse neighbourhoods (unique forms). Cognitive constraints in working memory or word retrieval may further affect consistency of output, especially as word length increases and word frequency (and familiarity) decreases (Stackhouse & Wells, 1997; Weismer, 1996).

Variability in phonological acquisition may thus derive from a number of factors, both internal and external to the phonological system (see also Rose, 2009). For some children with protracted phonological development (PPD), interaction of all of these factors may result in a higher than typical degree of variability, and even apparently random inconsistency (Dodd, Holm, Crosbie & McIntosh, 2010). The challenge for the speech-language pathologist (SLP) is to determine which aspects of a child's variable speech output may indicate incipient change, which may result from interactions between different components of the phonological and other cognitive and linguistic systems, and which may be random. Knowing more about the possible sources of variability can potentially lead to more fine-tuned intervention strategies.

The current paper describes a phonological system of an 8-year-old that showed a considerable amount of variability. A nonlinear analysis influenced by concepts of optimality theory (OT) and connectionism (discussed below) accounted for at least some of the variability. Production of words requires integration of a variety of independent but interactive levels of a phonological system within a particular context: segments (phonemes), syllable and word position (onset, nucleus, coda), overall word shape (CV sequences), word length, and word stress. The current paper demonstrates how interactions between the various elements can lead to patterns of variability.

The child in question had a rare metabolic condition that can have associated speech impairments: 3-Methylglutaconic Aciduria type I (3-MGA1) (Duran et al., 1982; Gibson et al., 1998). Minimal information is available on the speech of children with this condition, and thus, the paper also uniquely addresses that gap in the literature. The following sections provide a background on 3-MGA and an overview of major constructs in nonlinear phonology, OT, and connectionism that underlie the analysis.

3-Methylglutaconic Aciduria Type I

3-methylglutaconic aciduria type I is an autosomal recessive condition that results in impaired leucine degradation due to deficiency of 3-methylglutacon-coA hydratase (3-MGH) (Narisawa et al., 1986; http://ghr.nlm.nih.gov/condition/3-methylglutaconic-aciduria, July 18, 2011). Type 1 is the rarest sub-type (20 case reports in the literature). Currently, the condition is untreatable; however, leucine-restricted diets or L-carnitine supplements may benefit some individuals (Gibson et al., 1998; Gunay-Aygun, 2005; Illsinger, Lucke, Zschocke, Gibson, & Das, 2004).

The clinical features of this metabolic condition range from a mild phenotype, with reasonably normal development to a severe phenotype characterized by atypical neuromotor development (Gibson et al., 1998). Individuals with the severe form of 3-MGA1 have been reported to show considerable neurological damage, quadriplegia, and significant cognitive difficulties (Shoji et al., 1999). Individuals with the milder phenotype may display reduced attention, motor delays, frequent upper respiratory infections, and speech/language delays (Arbelaez, Castillo & Stone, 1999; Duran et al, 1982; Gibson, Lee & Wappner, 1992; Gibson et al., 1998; Hou & Wang, 1995; Shoji et al., 1999).

Nonlinear Phonology

Over the past 150 years, a variety of theoretical frameworks have been proposed to account for the world's speech sound systems. "Structural" linguists (de Courtenay, de Saussure, Trubetzkoy, Jakobson) developed strong theoretical foundations concerning the 'phoneme', as a composite of smaller units (features) concerning place, manner, and voicing. Through the mid-20th Century, "linear" rule-based (Chomsky & Halle, 1968) and process-based (Stampe, 1973/1979) theories were designed to account for broad generalizations across classes of phonemes, such as syllable-final devoicing of all stops or place assimilation in nasal-stop sequences, e.g., *ember* versus *tent* versus *finger* in English. Goldsmith (1976) observed, however, that the 'linear' theories could not account for all phonological patterns observed. Alternations occurred between elements that were not next to each other in speech output (e.g., vowel harmony across consonants, as in Hungarian); furthermore, there were iterative, multiple mappings, from one element to many others (where a specific tone could spread to a number of vowels distant from the originating tone location). Goldsmith thus posited an autosegmental, nonlinear phonological framework. This framework posits that phonological elements are hierarchically organized in addition to being in linear sequences. Elements at one level of the phonological 'hierarchy' can have their own set of conditions and operations, but, depending on their hierarchical position, can link to (be in association with) other 'tiers' (hierarchical levels) in the system that are not necessarily surface-adjacent neighbours like the nasal-stop sequences in English described above. Clements and Keyser (1983) suggested, for example, that consonants and vowels might actually be represented on separate tiers. Thus, vowel features can spread (be linked) from one vowel to another without being blocked by intervening consonants; the vowels are underlyingly adjacent neighbours on their own tier. Many phonologists have elaborated nonlinear phonology further (Hayes, 1989, 1995; Hyman, 1985; McCarthy, 1988; Sagey, 1986/1991, etc.).

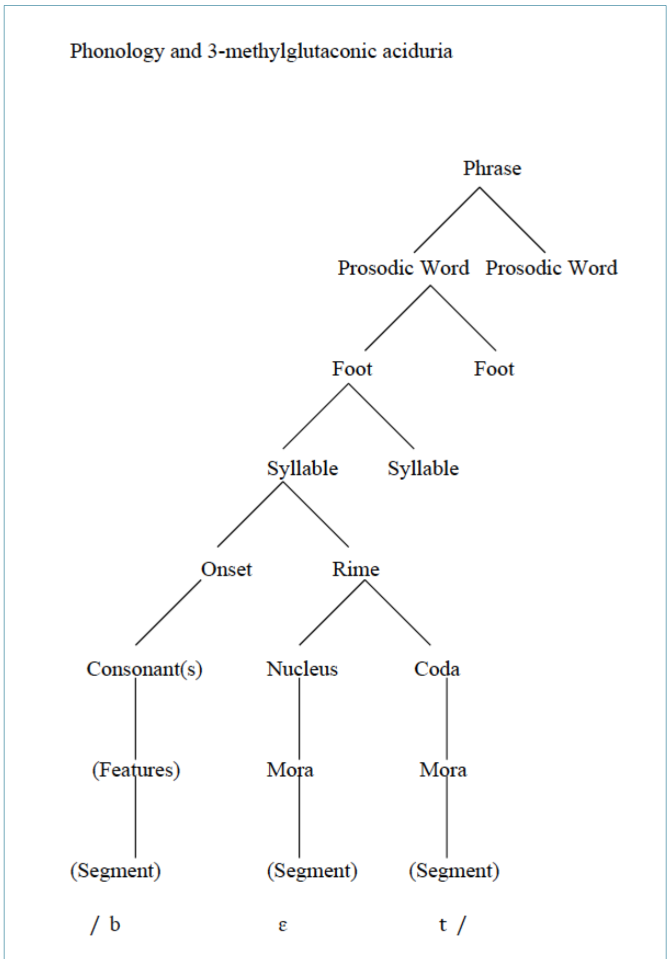

Figure 1. Hierarchical representation of the phonological structure from the phrase level to the Root level.

The phonological hierarchy is described as comprising at the lowest level, phonological features, with progressively larger and higher units: segments, syllable, foot, prosodic word, and phrase structures (see Figure 1), each with its own subordinate structure.

Beginning at the bottom of the hierarchy, Figure 2 and Appendix 1 describe the feature system used for the current paper, which follows Bernhardt and Stemberger (1998, 2000). Three *grouping* nodes account for the major components of segments: Root, Laryngeal, and Place. The Root node groups and links features to the prosodic structure above (in essence the Root is the 'segment'). Manner features link directly to the Root and in this way are arguably 'higher' in the hierarchy than place and laryngeal features, which have an intervening grouping node: Place or Laryngeal. The Laryngeal node dominates features such as [voiced], [spread glottis] and [constricted glottis], and Place node, the major feature categories Labial, Coronal, Dorsal, which in turn dominate more specific features, e.g., [Labial] dominates [round].

Each segment (consonant C or vowel V) is a composite of hierarchically organized features (Clements & Hume, 1995; McCarthy, 1988; Sagey, 1986/1991). The segments are grouped into syllables, which comprise a non-optional nucleus (the prominent unit, usually a vowel), an optional onset (syllable-initial consonant(s)) and an optional coda (syllable-final consonant(s)). The rime may include only a nucleus or a nucleus plus optional coda. Syllables are grouped into feet, with differing patterns of prominence. A left-prominent foot is stressed on the first syllable (e.g., <u>MO</u>-ther, <u>E</u>-le-phant), a center-prominent foot on the middle syllable (ba-<u>NA</u>-na) and a right-prominent foot on the final or penultimate syllable (e.g., gui-<u>TAR</u>). In English,

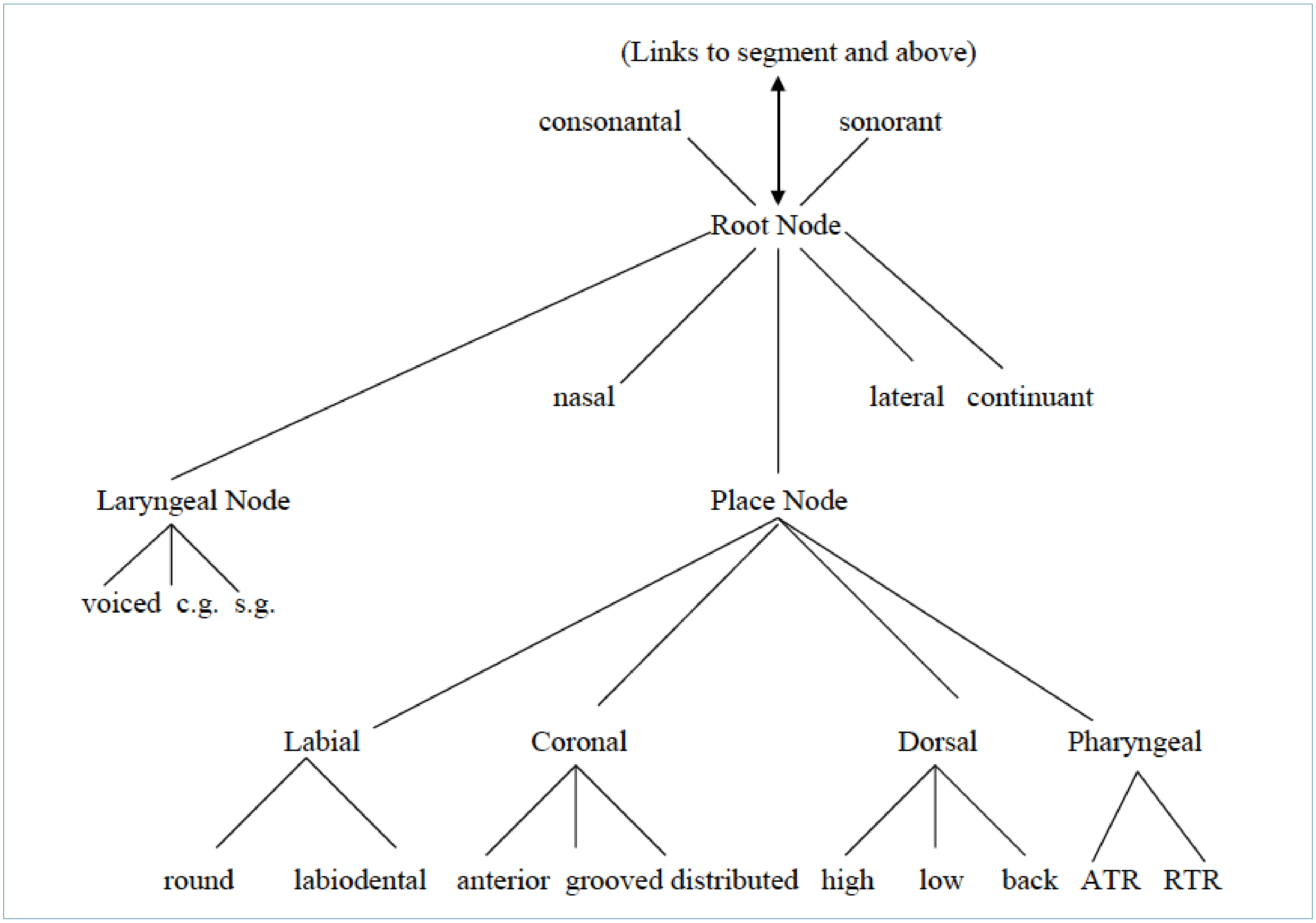

Figure 2. Feature hierarchy

words can have more than one foot. English prosodic words with secondary stress (and hence two feet) may have right prominence (MA-ga-ZINE) or left prominence (ALL-i-GAT-tor). (See also Kahn, 1976; Selkirk, 1980, 1982). For the current paper, primary stress is designated as S (strong; heavy), secondary with small 's' (stressed but less than S) and unstressed as (w: weak, light). Related to stress is the theory of phonological 'weight' (Hayes, 1989; Hyman, 1985; Stonham, 1990). Vowels and, in 'weight-sensitive' languages like English, syllable-final consonants can contribute to 'weight' ; in most cases, syllables with the most 'weight' in the rime, the 'heavy' syllables, are stressed. In English, for example, stressed syllables are generally bimoraic (long vowel, diphthong or lax vowel, and coda), and thus words such as /bɪ/ do not exist. The spelling of words such as *bitter/letter/mommy* is a hint that in older English there were geminate intervocalic consonants, creating a bimoraic first syllable (lax vowel and coda) (Hayes, 1989). Today the intervocalic consonant may be considered ambisyllabic (thus providing necessary weight to the first stressed syllable, and acting as an onset to the second) (Kahn, 1976), or the first syllable may simply remain stressed for historical reasons.

Markedness, nondefaults, and defaults

Within the phonological system, some elements are more common/less 'marked' than others. The concept of markedness was developed early on primarily by Trubetzkoy (1939) and Jakobson (1963), and has been further elaborated since, by for example, Chomsky and Halle (1968) and McCarthy and Prince (1986/1995). In terms of the prosodic hierarchy, less marked elements include left-prominent disyllabic words or monosyllables (versus multisyllabic words with centre- or right prominence), singleton consonants and vowels (versus clusters or diphthongs) and onsets (versus codas).

At the segment and feature level, languages both overlap and differ in phonetic inventory and feature sets and values (default/nondefault). For adult English, the default consonant is generally considered to be /t/ ([-continuant], [-voiced], [Coronal,+anterior]) (Bernhardt & Stemberger, 1998). However, children may have different defaults from those of adults. For example, Bernhardt & Stemberger (1998, 2000) describe a child (Colin) who had a [Dorsal] default, yielding a high proportion of velar substitutions in his system.

Nonlinear phonology and phonological patterns

As noted above, some phonological patterns occur between surface-adjacent segments (place assimilation of English nasals as in *number*), whereas others occur between elements that are not surface-adjacent, e.g., consonant harmony or assimilation across vowels: *duck* /dʌk/ → [gʌk], a pattern seen in child phonology but unattested in adult phonological systems, where vowel harmony across consonants is a more common phenomenon (Bernhardt & Stemberger, 1998). Elements may be grouped *together* in certain ways across the hierarchy, and these groupings can act as units in phonological patterns. For example, all syllable onsets may be deleted. All features dominated by the (Oral) Place node may be deleted, resulting in a substitution without oral place such as glottal stop or [h]. Although such patterns can be described, the question is how they occur. Are there stored procedures (rules/processes) mapping the input (or representation) to the output (production) or does change occur more on-line in response to certain restrictions in the system?

Basic Concepts in Optimality Theory and Connectionist Models

Prior to the advent of OT (Prince & Smolensky, 1993/2004; McCarthy & Prince, 1986/1995), abstract (linear) rules or processes were assumed (Chomsky & Halle, 1968; Stampe, 1973/1979). OT posits instead that output is a consequence of competition between interacting phonological constraints. The competition between constraints determines the output in a filter-like way. There is no direct rule manipulation. When the output (speech) matches the input (underlying form), it is 'faithful' to the underlying form, or alternatively, the input form 'survives' or 'passes through' the constraint/filter system. Thus, *big* /bɪg / is pronounced as [bɪg]. However, if markedness constraints (generally negative) are strong enough ('high-enough ranked'), they can inhibit production of the underlying forms. For example, if the feature [Dorsal] is not possible, but codas and oral stops must be produced, then *big* /bɪg/ may be pronounced as [bɪd], which would be labelled in process analysis as 'velar fronting'.

Thus, depending on the relative importance of other constraints in the system, a number of outputs are possible for a given input. For example, if clusters are not well-established in a system (there is a very 'high-ranked' complexity constraint), a number of possible outputs may occur, depending on the relative importance, or 'ranking,' of the other constraints in the system:

1. Assuming complexity is the highest-ranked, or the most important markedness constraint, one or both consonants may fail to surface, or 'delete'.
   blue /bluː/ [buː] or [uː]
2. If there is a high-ranked constraint requiring actual production of two consonants (timing unit faithfulness), but only when segmental content is simple (interactive constraints), one or both of the consonants may be replaced with another segment, either independently or through assimilation.
   blue [bjuː] or [vwuː]
3. If the complexity constraint is high-ranked but there is an equally high constraint requiring output of certain features, coalescence or epenthesis may occur: *blue* [vuː] or [bə'luː]. In the coalescence, the [Labial] of /b/ and the [+continuant] of /v/ are maintained while avoiding the cluster. In the case of epenthesis, the timing of the syllable is sacrificed for the production of the consonants.
4. Alternatively, if the contiguous sequence is not possible but certain features or segments must survive, migration or metathesis may occur: (less common) *blue* [buːl]

Formal OT posits tabular sets of constraint rankings to account for the observed output as compared with other possibilities (as shown by the different examples above). The current paper does not use formalism, but assumes two major basic OT concepts: (1) there is competition between elements throughout the phonological hierarchy (relative degrees of faithfulness versus markedness), (2) output is the automatic result of the interaction of those positive (faithfulness) and negative (markedness) constraints.

The concept of competition in OT above is also an active principle within the connectionist framework of language processing and learning. Smolensky (co-author of a major early OT manuscript, Prince & Smolensky, 1993/2004) had collaborated previously with key contributors to early connectionist models, Rumelhart, McClelland, and the Parallel Distributed Processing group (1986). Connectionist models view the processing of linguistic tasks as an interaction of activation patterns between neural networks (Presson & MacWhinney, 2010). In addition, these models hypothesize that linguistic processing occurs when activation patterns are dynamically spread between activated nodes (Dell, 1986)[1]. Language is processed in a multidirectional neural network in which the various domains of language (phonology, morphology, syntax, semantics, discourse) and cognition (e.g. attention, memory) interact. The dynamic language processing system is in a constant state of flux/competition whereby equilibrium must be established between activated nodes to ensure harmony of activation. Under- or over-activation of node(s) at any level within or between levels results in speech errors whereby outputs do not match adult targets. The effects of interactivity between levels or nodes can be seen in the following variable productions of one multisyllabic word from Dylan (aged 4;7, with protracted phonological development, PPD; Bernhardt & Stemberger, 1998, 2000). The word *together* /təˈɡɛðɚ/ appeared in conversation variably as [təˈɡɛə] [ˈɡɛ.dʊ] and [tʊˈɡɛ.dɪ]. The word *together* has multiple challenges: three syllables, an initial unstressed syllable, and two later-acquired segments, /ð/ and /ɚ/. As seen in the examples, stress and word length matched in one token, and the stressed syllable [ˈɡɛ] and its components were present in all three tokens. In the other two tokens, one or the other of the unstressed syllables deleted. Activation levels for those syllables were lower than for the stressed syllable, with overall activation of the final syllable low because of two negative (markedness) segmental constraints. The data for the current paper will illustrate further the effects of interactivity and different levels of activation on variability of output.

Further to output processing, only finite cognitive resources are available at any given moment in terms of attention, working memory, and the ability to manipulate elements (unconsciously or consciously). Linguistic processing is thus intrinsically limited by the availability of cognitive resources and capacity (see further discussion in Charest & Johnston, 2011; Kail & Salthouse, 1994). An imbalance or limitations in such resources impacts the ease at which linguistic processing can occur. Kolk (2001) argued that linguistic processing for children is limited due to the fact that their immature systems have limited cognitive resources available for such processing. During the learning period, variability in output is expected, as the activation level (relative strength) of more complex (marked, nondefault) elements gradually strengthens, and connections between various elements of the phonological (and other) systems become strengthened, i.e., between syllable position and feature, or foot and syllable, etc. Further discussion of connectionism is beyond the scope of the current paper. However, two integrated assumptions of OT and connectionism underlie the analysis for this paper and led to two major predictions for the case study.

Assumption 1. *Individual elements of a phonological system have different levels of activation* (Dell, 1986) *or strength* (described as different levels/ranks of faithfulness and markedness in OT). Elements that are more marked/uncommon/complex (non-prominent feet, codas, clusters, dorsal consonants, complex feature combinations such as voiced fricatives) will have lower activation (less strength, less opportunity for faithfulness) in early phases of development than less marked/more frequent/less complex elements. Weakly activated elements will either fail to surface (delete) or be replaced with the language's default forms (e.g., CV syllables, words with Sw stress patterns, default consonant [t]) or the child's own specific defaults (Bernhardt & Stemberger, 1998; Fikkert, 1994; Ingram, 1974; Levelt, 1994). For example, the Place feature [Coronal] dominates [anterior] and [grooved] (or [strident]). A child would be expected to produce segments with the default place feature [Coronal, +anterior] (e.g., /t/, /n/) before acquiring contrasts in anteriority (/s/ versus /ʃ/) or grooving/stridency (/s/ versus /θ/). The defaults [+anterior] and [-grooved] may replace the nondefault features.

> *Prediction 1: For individual phonological elements. A higher proportion of mismatch patterns was expected for marked (nondefault) versus unmarked (default) elements in English:* initial or medial weak syllables, codas, clusters, and late-developing consonants (liquids, coronal fricatives, and affricates; Smit, 2007).

Assumption 2. *Interactions between phonological levels can affect output (either increasing or decreasing faithfulness to input representations in output).*

As noted earlier, speech production requires integration of content from a variety of phonological levels. Features at the 'bottom' of the hierarchy, which may have intrinsically lower activation, will require higher degrees of activation in order to be produced in weak domains higher up in the hierarchy, such as weakly established word positions (e.g. codas), clusters, or unstressed initial syllables (Ullrich, Stemberger, & Bernhardt, 2008). If not sufficiently activated, a nondefault feature will not surface but either delete or be substituted with a sufficiently activated other nondefault or a default feature. On the other hand, strongly activated elements may enhance the faithfulness of a weakly activated element on another tier. For example, features may show higher activation in stressed syllables or shorter words. Fricatives and dorsal consonants may benefit from the strong activation of [+continuant] and [Dorsal] vowels, and thus emerge earlier between or after vowels (Bernhardt & Stemberger, 1998).

> *Prediction 2: Interactions. Lower accuracy was expected for elements in weaker environments*: i.e., long words, unstressed syllables, clusters, and diphthongs. Variability for a given element across the system would reflect those contextual differences at least in part (random variation always being possible).

Method

Participant

Max (pseudonym) was 8 years of age (Grade 3) at the time of the study. He lives in a bilingual Urdu/English household with his parents and siblings. Overall, he functions primarily as a monolingual speaker and thus the phonological profile described is based on his English. (An attempt to assess his speech production in Urdu was abandoned, because he appeared to lack basic labeling vocabulary in that language.)

In terms of education, Max has been in mainstream classrooms since kindergarten, with support from a resource teacher two to three times a week since Grade 1. He performs in the average range in academic subjects, with some difficulty noted for writing and spelling (although to date has had no psycho-educational assessment). Teachers describe him as a 'kind, friendly' child. Most language test scores within a year of the study were within normal limits: (1) Peabody Picture Vocabulary Test-IV (Dunn & Dunn, 2007): Scaled Score (SS) of 89 (mean 100), age 8;9; (2) Clinical Evaluation of Language Fundamentals (Semel, Wiig & Secord, 2003), Receptive Quotient SS 103 (mean 100), age 7;5; (3) The Expressive Vocabulary Test (Williams, 2007) score was slightly below average (SS 80, mean 100, age 8;9) but may have reflected his bilingual environment. The number repetition subtests of the CELF-4 showed possible constraints on working memory, with a significantly lower scaled score and percentile than average: SS 4 (SS mean 10, second percentile, age 9;8).

Max began receiving weekly speech/language therapy in kindergarten because of reduced intelligibility and limited utterance length (one to three word sentences). Treatment goals in kindergarten were to improve accuracy for CVC, disyllabic words, /f/ and /s/. In Grades 1 and 2 segmental treatment targets included dorsals (velars), affricates, liquids and diphthongs /aɪ/, and /eɪ/; word structure targets included /s/- and /l/-clusters, word-final consonants, and di- and multisyllabic words. Although Max showed gains over this period, his conversational intelligibility remained relatively low at age 8, and was exacerbated by a relatively rapid speech rate in conversation. In addition to his rapid speech, he had a general trend to do things in a hurried style, according to parent and teacher report.

Speech Evaluation

Assessment tasks for the current study included an oral mechanism evaluation, a connected speech sample and an audio-recorded 101-word single word elicitation (from the Computerized Articulation and Phonology Evaluation System [CAPES], Masterson & Bernhardt, 2001). The CAPES word list included a wide representation of English phonology (words up to six syllables) and was elicited through sentence completion tasks, or when necessary, through delayed imitation. All words were only elicited once; thus, the analysis was based on system-wide variability, not within-word variability. Five final-year Master's students in speech-language pathology performed narrow phonetic transcriptions by consensus in pairs or trios for the CAPES data. Included in the narrow transcription were stress marks, dentalization, aspiration, nasalization, and syllabic consonants (see Appendix 2). Vowel length was not confirmed acoustically. The single-word transcriptions were reviewed and confirmed by the second author (over 90% agreement). The connected speech sample was not phonetically transcribed because his rapid speech rate made it difficult to reliably agree on orthographic targets or pronunciations.

Oral mechanism examination

Max's oral mechanism revealed both typical and atypical features. The structure of his jaw, lips, palate, and tongue was unremarkable and there was normal function during some non-speech tasks, i.e., lip rounding, cheek puffing, and sustaining of /a/ (6 seconds). Structural differences included a few misaligned teeth and a closed bite. Functionally, he had restricted coordination of lateral tongue movement and tongue raising/lowering. He also demonstrated difficulty isolating the movements of his tongue and head, often moving his entire head in the direction of the targeted tongue movement. His diadochokinetic rate indicated a further area of difficulty according to the St. Louis and Ruscello (2000) Oral Speech Mechanism Screening Examination-Third Edition (OSMSE-3). The individual syllable repetition rate (papapa..., tatata..., kakaka...) was relatively slow, approximately two per second. The rate for sequences 'pata' and 'pataka' was also slow, approximately 1.5 per second, with voicing inconsistency for the stops and a perceptible lack of rhythmicity. The slow pace in his DDK tasks were a notable contrast with his rapid conversational speech rate, although a lack of prosodic rhythmicity was observed in both contexts. Whether the atypical oral motor features were a result of his metabolic condition is unknown, but they were likely related in some way to his speech production difficulties.

Developmental Nonlinear Phonological Analysis

Nonlinear phonological analyses examine speech output at the various levels of the phonological system, both in terms of inventories (independent analyses) and comparisons with the adult targets (relational analyses: see Baker & Bernhardt, 2004; Bernhardt & Stemberger, 2000; Bernhardt & Stoel-Gammon, 1994; Bernhardt & Zhao, 2010). Word structure analyses minimally include a description of inventories and deletion/insertion patterns concerning word length, prosodic word and foot types (stress patterns), and CV sequences (word shape, e.g. CVC as in bat). Additional sub-syllabic components may be described (onsets/codas/rimes/moras). For the segmental analysis, inventories and substitution/deletion patterns for consonants, vowels, and their features are described. Feature analyses examine features independently and in combination with other features.

A nonlinear analysis also examines interactions between constituents and levels of the phonological hierarchy. Context effects are examined in order to determine whether certain segments or features may be prohibited in certain contexts, particularly weaker prosodic contexts such as codas, clusters, or initial weak syllables. Assimilation and metatheses may imply that certain sequences of elements are prohibited, e.g., coronal-dorsal sequences, as in *dog*, or certain cluster sequences, e.g., s-clusters versus glide clusters.

Results

Individual Phonological Constituents

The phonological analysis first describes the smaller units at the bottom of the hierarchy for vowels, consonants, and their features, then discusses word position impacts for consonants, and finally higher word structure levels (word shape, length, feet, and stress).

Vowels and Diphthongs

Max produced all English vowels and diphthongs except rhotics /ɚ/ and /ɝ/, with an overall vowel match including diphthongs of 58%. (Diphthongs showed a 63% match.) Feature match for vowels (see Table 1) was 76% or better except for [-tense] (47.3% match). The mid vowels /ə/ (30.7%) and /ɛ/ (33.3%) showed the lowest match of the lax ([-tense]) vowels. Because vowel length was not acoustically confirmed, no further analysis concerning vowel length was done.

Table 1. Child's percent singleton vowel feature match, feature change, and vowel deletion

Feature	% match for feature or feature contrast[a]	% feature value change/ total targets	% vowel deletion/ total targets
[low]	76	21	3
[high]	86	4	9
[front]	76.3	17.5	6.3
[back]	82.2	7.5	2.5
[+tense]	86.6 (/67)	4.5	9
[-tense] (lax)	47.3 (/129)	29.5	23.3

[a] *Where both values had high match, the [+] and [-] data are combined.*

Vowel mismatches also included substitutions and deletions. Vowel deletion occurred 23% of the time for lax vowels (through weak syllable deletion), compared with 9% for tense vowels (often in stressed syllables). Diphthongs often showed monophthongization (24% of targets). The rhotic vowels showed more substitution (18/25 tokens distributed across [ə], [ɪ], [ʊ], [oʊ]) than deletion (7/25 tokens). With the exception of two words with weak initial stress (again, balloons), the majority of weak syllable (vowel) deletion occurred in words of three or more syllables that included syllables with secondary stress.

Singleton Consonants

The overall match proportion for singleton consonants in the 101-word list of the CAPES (Masterson & Bernhardt, 2001) was 37%. Word-initial position showed the highest match (55% overall), word-medial and word-final about the same proportional match (31%), with decreasing accuracy by word length. (See Table 2.)

Consonants in his phonetic inventory included all stops, nasals [m] and [n] (and one [ŋ] metathesized in *swimming* as [s̥ĩŋĩn]), labiodental fricatives [f,v], coronal fricatives [s,z],

Table 2. Child's percent singleton consonant (C) matches, substitutions, and deletions by word length and position

Word length	Word position	Total C targets	% match	% substituted	% deleted
Monosyllabic	Word-initial	22	50	50	0
	Word-final	22	45	36	18
Di- or multi-syllabic	Word-initial	54	59	39	2
	Word-medial	164	31	34	35
	Word-final	55	25	17	58
Total		317	37	33	30

Table 3. Child's consonant inventory by place and manner of articulation

Manner of Articulation	Place of articulation				
	Labial		Coronal		Dorsal
	Labial	Labiodental	[+anterior]	[-anterior]	
Stop	p b		t d	ɟ[a]	k g
Nasal	m		n		ŋ
Tap			ɾ		
Fricative		f v	s z		h
Glide	w	ʋ[a]			
Lateral			l	ʎ[a]	

[a]Non-English substitutions

lateral [l], flap [ɾ], and glides [w] and [h] (see Table 3). Only /w/ and /h/ showed 100% match (and only occurred word initially).

The consonants in his inventory comprised most major manner classes (absence of affricates and /ɹ/). If the consonant was not deleted, major place features matched most of the time, even if the manner or laryngeal features showed mismatches: [Labial] ([round] and [labiodental]); Coronal [+anterior] (alveolar); and Dorsal (velar stops and nasal). Voicing contrasts were observed for stops and fricatives although less consistently than for major place (see positional data below).

As seen in Table 4, absent from the consonant inventory were fricatives /θ, ð/, affricates /tʃ,dʒ/, and approximants /j/ and /ɹ/ (both considered glides, as in, e.g. Bernhardt & Stemberger, 1998). For place features, this implied absence of [-grooved] for the interdentals and [-anterior] for the affricates and glides, and for manner features, absence of the sequence [-continuant]-[+continuant] for the affricates.

been influenced by the variability in /v/ production in Urdu and the palatals as an influence of the high proportion of retroflexed consonants in Urdu (Saleem et al., undated, Centre for Research in Urdu Language Processing).

Consonant positional constraints

Word position was relevant for consonant production as follows:

1. Word initially, there was 100% match across a variety of manner categories, for some coronal and labial targets and for some voiced and voiceless obstruents: glides /w/ and /h/, sonorants /m/, /n/, and /l/, stop /d/ and fricatives /f/ and /z/. Word finally, labial obstruents /p/ and /f/ showed 100% match. Word medially, no consonant was 100% accurate, although /b/ was accurate 66.7% of the time.
2. For stops, the dorsal stop /g/ was absent word finally, and /d/ and /b/ were inconsistent word finally.
3. Fricatives: Missing by word position were word-medial /s/ and word-final /z/ and /v/. In terms of the feature combination [+continuant]&[-sonorant] (defining fricatives), there was a split between match levels for word-initial (70.6% match) versus word-medial (21.1%) and word-final (16.7%) positions.
4. Voicing contrasted in accuracy also in terms of word position, with word-initial and word-medial (intervocalic) consonants having more in common. Word initially and medially, [+voiced] was relatively well-established for stops and fricatives (100% and 93.3% respectively), but word finally, deletion, or devoicing resulted in only a 15.4% [+voiced] match. In contrast, [-voiced] obstruents matched for [-voiced] 54.2% of the time word initially and 42.9% of the time word medially (with voiced substitutions, or in word-medial position, consonant deletion) and 81.3% word finally (with mismatches attributable to consonant deletion).

Table 4. Consonants missing from the child's phonetic inventory by word position and manner category

Word Position	Stops/Nasals	Fricatives	Affricates	Glides
Initial		θ ð ʃ	tʃ dʒ	j ɹ
Medial		s θ ð	tʃ dʒ	ɹ
Final	(d) g ŋ	v z θ ð ʃ ʒ	tʃ dʒ	ɹ

Mismatch patterns included both substitution (33% of total targets) and deletion (30%), often for the same category. Fricatives were deleted or substituted with stops or other fricatives; /ɹ/ was deleted or substituted with [w] (onset), or with a vowel (coda). A greater proportion of coda deletion occurred in words of two or more syllables (58%:17% ratio, deletion:substitution), than in monosyllables (18%:36% ratio). Syllabic consonants /l̩ n̩, ɹ̩/ often reduced to [ə], thereby maintaining their prosodic constituency as syllable nucleus, but losing their characteristic features.

Many of the observed mismatch patterns were typical developmental patterns (see Bernhardt & Stemberger, 1998, Chapter 5), but non-English consonants also surfaced occasionally as substitutions: the labiodental glide [ʋ], the voiced palatal stop [ɟ] and the palatal lateral [ʎ]. These may have been arisen as a result of his exposure to Urdu or Urdu-influenced English; the labiodental glide may have

Table 5. Child's word shape match for words with and without clusters (1-3 syllable words)

Type	Word length (# syl)	Word shape	Total targets	% match
No CC	1	CV(V)	2	100
		CVC	13	100
		CVVC	5	40
	2	VCVC	1	0
		CVCV	3	100
		CVCVC	11	18.2
		CVVCVC	1	0
		CVCVVC	1	0
	3	CVCV(V)CV(V)	3	33
		(C)V(V)CVCV(V)C	6	16.7
With CC	Monosyllables	CCV(C)	4	0
		CVCC	2	0
	Di- and multi-syllabic words	Word-initial CC	8	12.5
		Word-medial CC	25	16
		Word-final CC	3	0
Total up to 3 syl.			88	31.8

Note. Words of 4+-syl (13 tokens) showed no word shape matches.

Word Structure

Word shape (CV sequences)

Moving up the phonological hierarchy, Table 5 shows word shape data, i.e., accuracy of CV sequences. Overall word shape match was 27.7%; for words of up to 3 syllables, overall match was 31.8%; words of four syllables or more had no word shape matches.

Basic word shapes (CV, CVC, CVCV) showed 100% match. Word structure complexity (consonant sequences/clusters, codas, diphthongs) was associated with reduced word shape accuracy. Match proportions for consonant sequences (clusters) overall was 6% (573 targets). Word-initial and -medial clusters showed an 8% match for timing units (CC) but there were no word-final clusters.

Mismatch patterns for word-initial and -medial clusters generally involved deletion of the second consonant, C2: a deletion rate of 54% for word-initial clusters, and 36% for word-medial clusters, compared with an 8% deletion rate for C1. Substitution also occurred 30% of the time in clusters. Over 56% of word-final clusters were deleted entirely, with 22% showing deletion of C2, and 11%, a substitution or deletion of C1. Reduction patterns resulted in a high proportion of words without codas or clusters, such as CVC, CVCV and CVCVCV (V includes diphthongs). Examples are given below. The adult pronunciation (input to the child) is based on the local dialect area of Vancouver, Canada.

Word	Adult pronunciation	Child	Patterns
balloons	bəˈlũnz	ˈlus	Deletion, initial unstressed syllable; Word-final CC > C; CVCVCC > CVC
fishing	ˈfɪʃĩŋ	fɪˈdɪ	Stress shift, CVCVC > CVCV
hospital	ˈhɑspɪɾl̩	ˈhɑbɪdə	Medial CC>C; Syllabic /l̩/ > [ə] CVCCVC(V)C > CVCVCV

Word length, feet and stress

Table 6 shows Max's word length, foot, and stress pattern match proportions.

Word length match was 60.8% overall. With increasing word length, there was a concomitant decrease in match for length: 100% match for monosyllables, 79.3% match for disyllables, and 53.3% match for multisyllabic words (although he could produce words of up to five syllables, e.g., *hippopotamus* [ˌhɪˈpʰoʊˈpʰeɪʔɪ.ə]). Most frequent prosodic words had one foot with left prominence. For all words but explodes, which had final vowel epenthesis ([ʔɛˈʔpoʊdə]), length mismatch patterns involved deletion of primarily weak syllables. Across all words, 31% of weak syllables were deleted. By stress pattern and word length, weak syllable deletion occurred over total words per category as follows: wS disyllabic words - 3/12 words; trisyllabic words - 9/20, with least for wSw (0/6) and most for Sws (5/5); 4/5-syllable words - 7/22.

Table 6. Child's word length, foot, and stress pattern match proportions

Word length (# syl) and overall match	Total targets	% match: Length	Foot type: # - prominence	Stress type	% match: Stress
1	27	100	1	S	100
2	5	100	2 - L		60
	12	83.3	1 - L	Ss	58.3
	6	83.3	2 - R	Sw	50
	6	50	1 - R	sS	50
3	5	80	1 - L	wS	80
	5	80	2 - L	Sww	40
	5	0	2 - L	Ssw	0
	5	60	2 – R	Sws	0
	5	40	2 - R	sSw	20
	7	85.7	1 – R	swS	42.9
Overall %, 1 syl.	27	100			100
Overall %, 2 syl.	29	79.3			55.2
Overall %, 3 syl.	32	59.4			31.2

Table 6 continues on the next page

Table 6 (continued)

Word length (# syl) and overall match	Total targets	% match: Length	Foot type: # - prominence	Stress type	% match: Stress
[a]Overall %, 4+ syl	13	23		Various[a]	0
Overall %, 2-4 syl.	74	60.8			35.1
Overall %, 1 Ft (2+ syl)	30	53			
Overall %, 2 feet	31				31
Overall %, L Foot	32				32
Overall %, R Foot	29				29

Note: L= left-prominent (trochaic); R=right-prominent (includes center-prominent in this table, because both right- and center-prominent feet contain initial syllables with weaker stress on the left). S=strong, primary stress; s=secondary stress; w=weak or unstressed.
[a]One token each except Swsw (two tokens); length matches for wSsw, wSww, swSww.

In contrast with word length, word stress showed a lower match proportion of 35.1%. In addition to syllable deletion, other stress/foot mismatch patterns were observed: stress equalization (36.4% of opportunities) and stress shift (44% of opportunities). For example, *banana* /bəˈnænə/ (weak-Strong-weak, wSw) was produced as [ˈbiˌnæˌna] (Strong-secondary-secondary, Sss), showing stress and prominence shift, stress equalization, and foot mismatch (one > three feet). Stress shift often affected location of prominence as in *banana*, but not in all cases. If a weak syllable is pronounced with secondary stress or vice versa, both still have lower prominence than the syllable with primary stress. Thus, *mosquito* remained centre-prominent even though the first syllable was pronounced with secondary stress (in a two-footed word): /məˈskiːɾoʊ/ → [ˌməˈkeɪɾĩn].

Stress mismatches were more common in words of three or more syllables, especially those with secondary stress, where only 3 of 43 words matched for stress. However, disyllabic words also showed stress equalization or stress shift, e.g., *muffin* [ˈmʌˈdoʊ] (equalization, and creation of two feet) and *fishing* as [fɪˈdɪ]) (stress shift, prominence change from left- to right-prominent). Interactions of stress and other structural aspects of the phonology were thus relatively frequent.

Discussion

The current paper had two major objectives: (1) to illustrate a phonological system with notable variability, using a nonlinear phonological analysis influenced by Optimality Theory and connectionist models, and (2) to describe the speech characteristics of a child with 3-MGA1. The non-phonological aspects of Max's assessment profile are discussed first in order to provide a context for the ensuing discussion of his phonological system, which addresses both individual elements and interactions between components of the phonological system.

Non-Phonological Factors and Speech Output

Non-phonological factors associated with Max's phonological output were: (1) limited skills for repetition of diadochokinetic sequences and for voluntary tongue lateralization, elevation, and lowering, (2) a rapid speech rate in conversation as a reflection of a general 'hurried' or unfocused style of behaviour, and (3) below-average performance on number repetition tasks. Whether those factors are characteristic of the particular metabolic condition is unknown, although motor difficulties are mentioned as sometimes characteristic. Beyond this particular condition, Van den Berg (2006) notes, in a kinematic study of children with suspected childhood apraxia of speech or PPD: "A matured and skilled motor control system should be able to select the most optimal speech condition; one that is flexible but at the same time stable. A non-optimal condition would be rigid or highly variable, leading to inconsistent speech characteristics…" (p. 76). Being able to execute a place sequence (*pataka*) accurately requires a stable motor plan and consistent implementation in which the various segments interfere minimally with each other at higher rates of articulation. His DDK results and restricted tongue movements thus suggest some degree of functional motor planning and implementation difficulty, which was probably also related to his reduced accuracy in longer words. Another factor that affected his intelligibility and probably also his attention to phonological input, was a hurried, unfocused style, demonstrated by his rapid speech rate in conversation, which can itself lead to a greater number of speech errors. A third factor was his reduced capacity in phonological working memory. Holding a potentially interfering set of syllables for continuous rapid repetition (DDK) within a phonological working memory with limited capacity likely resulted in reduced accuracy for such sequences. The relationship between motor planning, phonological working memory, attention/focus, and speech production has yet to be clearly defined, but all of these factors were at least associated with his speech output, discussed in the following two sections.

Individual Phonological Elements

> *Prediction 1: With regard to individual phonological elements, a higher proportion of mismatch patterns was expected for marked (nondefault) versus unmarked (default) elements in English*: initial or medial weak syllables, codas, clusters, and late-developing consonants (liquids, coronal fricatives, and affricates).

By age 8, most children have mastered the majority, if not all aspects of English phonology (Smit, 2007). Max did show mastery of basic phonological form: CV, CVC, CVCV, and most major manner, place, and laryngeal features, although not always in combination with one another. Thus, a segment might show match for place, but not for laryngeal or manner features. He continued to show difficulty with later-acquired consonants, some vowels, more complex word shapes, longer words, and stress. Most of his segmental mismatch patterns were typical: stops for coronal fricatives and affricates, glides for liquids, fronting of palatoalveolars or dorsals (Smit, 2007). Many of the mismatch patterns affecting word structure were also typical for English: deletion of unstressed syllables in long words, deletion of codas and cluster consonants, monophthongization of diphthongs (Smit, 2007).

Complexity appeared to affect segmental output. Consonants absent from the inventory (affricates, /ɹ/, interdentals) could be seen as complex in terms of feature sequences or combinations: affricates have a [-continuant]/[+continuant] sequence within one segment; interdentals, a combination of [-grooved] & [+continuant] (where stops /t/ and /d/ are [-grooved] & [-continuant]); /ɹ/, complex place [Labial]- [Coronal] (& arguably [Dorsal]) and /j/, complex place [Coronal]-[Dorsal] (see Appendix 1 for a brief discussion of feature-segment correspondences concerning glides). Thus, for the most part, both his inventory of forms and his mismatch patterns were as predicted: nondefault (marked) elements were still being acquired, and either were deleted or replaced by default forms.

Two prosodic mismatch patterns were less typical for English acquisition, i.e., stress shift and stress equalization. Stress equalization has been noted in early typical development in Dutch (Fikkert, 1994) and Mexican Spanish (Hochberg, 1988). However, the degree to which these patterns occurred in Max's sample was unusual for English acquisition. The bilingual context of acquisition may have affected stress development (as noted by Paradis, 2001 for French-English bilinguals). However, the difficulties observed for the DDK may also be relevant; some children with motor planning and implementation difficulties also show atypical stress patterns (Van den Berg, 2006). His rapid speech rate in conversation may also reflect difficulty in monitoring suprasegmental prosodic aspects of speech production.

Interactions between Phonological Elements

> *Prediction 2: With regard to the interactions between phonological elements, lower accuracy was expected for elements in weaker environments, with variability reflecting context, at least in part* (i.e., long words, unstressed syllables, clusters and diphthongs).

Interactions between phonological elements at various levels can result in higher or lower accuracy of the individual elements. Well-established (high activation) elements at one level (over 75-80% match) can potentially enhance production of less well-established elements at another level. Interactions can also have a negative effect on output: elements that are marginal in the system (rarely accurate, low activation) will not be sufficiently strong to activate accurate output at another marginal level. The following discussion addresses in turn various interactions observed in Max's phonology: word position effects, other segment-structure interactions, and prosodic interactions: word length-word shape, foot structure, morphology, and word shape. Examples are drawn from Appendix 2 for each interaction type.

Word position is a common source of system-wide variability concerning segment-structure interactions (e.g., Inkelas & Rose, 2007; Marshall & Chiat, 2003). For

Max, singleton fricatives were less likely in codas and as onsets to unstressed syllables than as onsets in the more well-established stressed syllables. For example, voiced fricatives /v/ and /z/ appeared as onsets in stressed syllables (a well-established position), but not word finally (a weak position, where they either deleted or were realized as stops) as the following tokens show:

Word	Adult pronunciation	Child	Patterns	
van	vǣːn	vǣːn		BUT
glove	glʌv	gʌp	Voiceless stop for fricative	
zipper	ˈzɪpɚ	ˈzɪˈpoʊ		BUT
nose	noʊz	noʊ	Coda deletion	

The /ʃ/ retained its [+continuant] feature in word-initial onset but not elsewhere in the word.

shoe	ʃuː	s̺uː		BUT
fish	fɪʃ	fɪt²	Stop for fricative	

Similarly, /l/ was accurate word initially, but still developing in other positions.

Word	Adult pronunciation	Child	Pattern	
laugh	læːf	læːf		BUT
lemonade	ˌlɛməˈneɪd	ˌlɛˈmeɪ		BUT
animal	ˈ(ʔ)æːnəml̩	ˈ(ʔ)æːnɪmʌl	Vowel epenthesis before [l]	
whistle	ˈwɪsl̩	ˈwɪdɛ	Vowel replacement of /l̩/	
violin	ˌvaɪəˈlĩn	ˈfaɪˌlĩn	Match: stressed	BUT
skeleton	ˈskɛlərn̩	ˈsʌ.ɛ̃.ĩ	Deletion of /l/: unstressed	

Stops were also not immune to positional constraints, with voicing in particular reflecting the word position (higher proportion of [+voiced] obstruents word initially and medially compared with word finally, and vice versa for [-voiced]).

Segmental constraints also appeared to interact generally with word shape production, particularly for words with codas or clusters. CVCVC appeared to be in and for itself a relatively weakly established word shape: 82% of these targets were produced without a coda. However, an examination of the segments in the CVCVC words showed that 87% of the words with coda deletion included target consonants missing from his phonetic inventory, e.g. *fishing*, where /ʃ/ was absent from the inventory: /fɪʃĩŋ/ [fɪdɪ]. This suggests an underlying effect of inventory constraints on output of the word as a whole (low activation for the unestablished target consonants failing to strengthen output of the weakly established coda). In the case of clusters, segments that were present in the phonetic inventory as singletons often deleted. (See *glove* above.) In this case, the complexity of the cluster inhibited production of an achievable segmental target. Generally, the least sonorous element was maintained in a cluster, but there were exceptions, creating further system-wide variability.

Word	Adult pronunciation	Child	Patterns	
star	ˈstaɹ	ˈdaʊ	Fricative deletes	
queen	ˈkwĩn	ˈgĩn	Glide deletes, voicing of /k/	
slide	ˈslaɪd	ˈsaɪ	/l/ deletes: /s/ less sonorous	BUT
skeleton	ˈskɛlətn̩	ˈsʌ.ɛ̃.ĩ	/k/ deletes: /k/ less sonorous	

Segmental factors also showed interactive patterns with stress. One relatively uncommon word stress pattern for English is Sww (even though left-prominent).

Word	Adult pronunciation	Child	Pattern	
hospital	[ˈhɑspɪɾl̩]	[ˈhapɪdə]	Sww	BUT
furniture	/ˈfɝnətʃɚ/	[ˈfʊdɛ]	Sww > Sw	

The word *hospital* showed stress and word length match but deletion of /s/ word medially and schwa for syllabic /l̩/. The word *furniture*, in contrast, had a stress and word length mismatch, with medial weak syllable deletion, and substitutions for the affricate and rhotic vowels. The less frequent word *furniture* contains rhotic vowels and an affricate, both consonant types missing from Max's phonetic inventory, whereas the more common word *hospital* contains consonants that he produced in other words, and thus, had higher activation. Negative segmental constraints may have decreased the overall potential accuracy of *furniture*, a stress-length-segment interaction. A similar interaction may have affected *umbrella*: /ˌʌmˈbɹɛlə/ [ˈʌˌbʌˌbʌ], a trisyllabic word with centre prominence, a /bɹ/ cluster, /l/ and two lax vowels. Complexity was reduced by: (1) harmonizing all vowels to [+tense] [ʌ], (2) reducing /bɹ/ to [b], (3) increasing the foot number to three, each containing a syllable with some degree of stress, (4) shifting stress to left prominence and (5) reduplicating the last two syllables. Reduplication was an infrequent mismatch pattern for Max, but enabled maintenance of word length with reduced complexity. Sacrificed were the consonant sequences, the lax vowels and the stress/foot patterns.

Turning to the higher levels in the phonological hierarchy, more general interactions were observed among prosodic factors. For example, word length also affected word shape. As word length increased, word-final coda deletion also increased generally: 10% coda deletion in monosyllables, 37.5% in disyllables, and 57.9% in multisyllabic words. Even though a word-final coda might appear in a monosyllable, the same coda had a tendency to delete in longer words. The example with *house* shows equal stress for the monosyllable and disyllable, and thus, even stress could not rescue the codas of *doghouse*. The diphthong also became less accurate in the more complex compound word (two codas and a diphthong).

Word	Adult pronunciation	Child	Patterns
house	ˈhaʊs	ˈhaʊt	Fricative deletes
pig	ˈpʰɪg	ˈbɪk	Coda [Dorsal], devoiced BUT
doghouse	ˈdɑːgˌhaʊs	ˈdɑːˈhoʊ	

(Compare also *van* and *muffin* in Appendix 2.)

A similar effect of word length was noted for word-medial consonant deletion, which occurred in 31.9% of multisyllabic words but not at all in shorter disyllabic words.

Foot structure, morphology, and word prominence type also showed trade-off interactions as in the examples below with *raccoons*, *balloon*, and *balloons*.

Word	Adult pronunciation	Child	Patterns	
raccoons	ˌɹæˈkʰũːnz	ˈwæˌgu	CC deletion	BUT
balloons	bəˈlũːnz	ˈlus	C1 deletion	BUT
balloon	bəˈlũːn	blũːm	Vowel deletion	

The words *raccoons* and *balloon*(s) both have right-prominent stress but *raccoons* has secondary stress in the left-most syllable (and two feet), which thus has higher activation in the first syllable. For *raccoons*, word length and foot number were thus maintained, although stress shifted to the more common left-prominent type. The now less prominent second syllable (similar to *doghouse* above) showed coda deletion, weaker syllables having lower activation for more complex word shape elements. The word *balloons*, in contrast, had mismatches for length and stress, but a singleton coda [s] in the stressed syllable (i.e., the opposite of *raccoons*). The plural morpheme appeared rather than the base phoneme /n/, suggesting a higher-ranked faithfulness to morphological form than phonological form, given sufficient syllable prominence. The /b/ of *balloons*, although generally strong in his system, could not 'rescue' the weak initial syllable in a marked right-prominent stress type, in a word which also had a plural morpheme (additive morphological and phonological complexity). The stress and word length were not maintained in the singular form *balloon* either, but more consonants appeared, including a non-target /bl/ cluster. Simplification was evident for the segments: /n/ surfaced as [m], showing progressive assimilation from onset to coda. Thus, in both *balloon* and *balloons*, the /n/ (with its default Coronal place) appeared to have low activation. Interestingly, the /l/, another coronal sonorant, was maintained in both the singular and plural (even though it deleted in words like *glove*).

Summary and Conclusion

Overall, Max, an 8-year-old with 3-MGA1, showed both typical and atypical speech patterns, the latter in particular concerning prosodic characteristics (stress, rate). The variability in his data at least in part reflects effects of aggregated complexity across phonological levels, as the examples in the previous section show. His speech output was also potentially influenced by other factors (motor planning and implementation skills, working memory), and word familiarity (lexical frequency, which is lower for most multisyllabic words in English, and therefore less practiced). According to an interactive processing model (Bernhardt & Zhao, 2010; Dell, 1986), low activation for units at one level will provide insufficient activation to support other units with similarly low activation at other levels. That is, segments absent from output inventory, even if present in underlying representation, have low activation, and therefore are less likely to bolster the production of higher level structure; if higher level structures also have lower activation, the potential for accurate output at both levels is decreased. Max's data exemplify these interactions within a developing phonological system challenged by multisyllabic word production (in some cases, even words with two syllables).

The study is necessarily limited by being a single-point case analysis, based on single-word elicitation of 101 words. Further testing of the individual was not possible at the time, but additional information on his speech processing skills would possibly be illuminating, given the reduced digit span recall and lower DDK scores. Future research will require larger sample sizes in terms of participants and data sets, with purposeful manipulation of length, stress, word shape and segment types and more in-depth examination of output and input phonological processing and memory skills. In addition, it might be informative to compute lexical, phoneme, and phonotactic frequencies, and evaluate the phonological neighbourhoods of the various words elicited in order to evaluate those effects more specifically.

There are several clinical implications of these data. First, when examining phonological profiles, Max's profile suggests that it is important not only to analyze productions at the level of the segment, syllable, or foot, but also to look for possible interactions between phonological levels, in order to account for variable patterns. Complexity or absence of an element at one level can result in degrading of the total output, or a trade-off in production, whereby one element survives at the expense of another. This is particularly important in later development, when the client may be attempting longer words, where complexity aggregates across levels. Assessment tools need therefore to target segments in words of various lengths, shapes, and stress patterns/feet (James, 2006). By extension, treatment word lists could be designed with varying complexity/difficulty in terms of segments, word shapes, stress patterns, and length. Some children may be able to learn late-developing segments in complex and long word shapes with initial weak syllables and clusters, but other children will require a careful scaffolding of complexity across the various levels of the phonological system. This report exemplified effects of interactive complexity across various levels of a phonological system, at the same time providing a speech profile of a child with the rare condition, 3-MGA1.[3]

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Declaration of Interest Statement

The second author is a co-author of the Computerized Articulation and Phonology Evaluation System (Masterson & Bernhardt, 2001), which was used for the phonological assessment. The authors now own copyright and the program will soon be available for free to certified speech-language pathologists upon request.

End Notes

[1]The term 'node' as used in feature geometry may or may not have similar connotations as the nodes of connectionist models, which are loci of potential connections between elements.

[2]Word-final fricatives can emerge earlier than fricatives in other positions, possibly because of a rime constraint promoting [+continuant] (Bernhardt & Stemberger, 1998;

Dinnsen, 1996). In this case, the target was a low-frequency palatoalveolar /ʃ/, a late-developing phoneme in English and for this child. It is not clear that there is a coda-first option for all fricatives, once the basic notion of fricative has been acquired (and he already had /f/ and /s/ which could occur word initially and finally). For him, codas were a weak environment, and default features more likely in those contexts.

[3]Following this assessment study, Max continued to receive speech-language services through the school system. Treatment included a focus on syllable structure, word length (up to 6 syllables), speech pacing, including through Morse Code, and production of unacquired speech sounds. He is continuing to improve in speech production and remains more intelligible at the single word level and within shorter sentences than in longer utterances, especially when he monitors his rate, which he is learning to do.

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APPENDIX 1.

Consonants features and segment groups

Feature	Default?	Consonants
Manner		
Glides: [-consonantal]		j w ɹ h [ʔ]
([+sonorant][+continuant])		
Flap [+consonantal] [+sonorant]		ɾ
Liquid lateral: [+lateral]		l
Nasals: [+nasal] ([-continuant])		m n ŋ
Stops: [-continuant] (& [-nasal])	yes	p b t d k g ([ʔ])
Fricatives [+continuant] (& [-sonorant)		f v θ ð s z ʃ ʒ
Affricates [-continuant],[+continuant]		tʃ dʒ
Place		
Labial (lips)		p b m f v w (ɹ)
Labiodental		f v
Coronal (tip and blade consonants)		
[+anterior] (dentoalveolar)	yes	t d n ɾ θ ð s z l
[-anterior] (post-alveolar)		ʃ ʒ tʃ dʒ ɹ j
[+grooved] ([+strident])		s z ʃ ʒ tʃ dʒ
[-grooved] ([-strident])	yes	θ ð
Dorsal (velar)		k g ŋ j w (ɹ; l in velarized contexts)
Coronal-Labial-(Dorsal)		ɹ (l in velarized contexts, with or without [Labial])
Coronal-Dorsal		/j/
Laryngeal		
[-voiced]	yes	p t k f θ s ʃ tʃ
[+voiced] stops and fricatives (obstruents)		b d g v ð z ʒ dʒ
[+spread glottis]		h p^h t^h k^h f θ s ʃ tʃ
([+constricted glottis]		[ʔ])

Note. Feature defaults are for adult English. Children may have different defaults.
[a]Following Bernhardt and Stemberger (1998, 2000), glides are represented with more than one place feature. The /w/ and /j/ are considered equivalent to vowels /i/ and /u/, but realized in onset. Thus, they are designated with [Dorsal] (tongue body) and either [Labial] (/w/) or [Coronal]-[-anterior] (/j/). The English /ɹ/ is also designated as [Coronal][-anterior] with some degree of lip rounding, i.e. [Labial]. Whether there is a [Dorsal] or [Pharyngeal] component is arguable, but on ultrasound, there appears to be retraction of the tongue body and root in addition to bunching or retroflexion of the tongue body or blade (Bacsfalvi, 2010).

APPENDIX 2.

Child pronunciations organized by word length, stress, and onset manner and place

Word Length Stress	Manner Initial C	Word	Adult Pronunciation	Child Pronunciation
1 syllable (S)	Stop	pig	pʰɪg	bɪk
		book	bʊk	bʊk
		teeth	tʰiθ	dit
		toe	tʰoʊ	doʊ
		toes	tʰoʊz	doʊ
		tree	tʰɹiː	tʰiː
		tub	tʰʌb	dʌp
		duck	dʌk	duk
		cage	kʰeɪdʒ	gæt
		queen	kʰwĩːn	gĩːn
		gum	gʌ̃m	gʌ̃m
		glove	glʌv	gʌp
	Nasal	nose	noʊz	noʊ
	Fric/affric	fish	fɪʃ	fɪt
		van	væ̃ːn	væ̃ːn
		thumb	θʌ̃m	dʌ̃m
		that	ðæːt	dɛt
		slide	slaɪd	saɪ
		soap	soʊp	s̪oʊp
		star	staɹ	daʊ
		shoe	ʃuː	s̪uː
		jam	dʒæ̃ːm	ɟæ̃ːm
	Lateral	laugh	læːf	læːf
	Glide	hand	hæ̃ːnd	hæ̃ːn
		house	haʊs	haʊt
		watch	wɑːtʃ	wɑːt
		yard	jaɹd	lɑː

2-syl Sw	Stop	pages	ˈpʰeɪdʒəz	beɪt
		present	ˈpʰɹɛzn̩t	ˈbʌɾɛ
	Nasal	mommy	ˈmʌmi	ˈmʌmi
		muffin	ˈmʌfn̩	ˈmʌˈdoʊ
	Fricative/ affricate	feather	ˈfɛðɚ	ˈfɑːdoʊ
		fishing	ˈfɪʃĩŋ	ˈfɪdɪ
		swimming	ˈswɪmĩ{ŋ/n}	ˈs̪ɪŋĩŋ̪
		zipper	ˈzɪpɚ	ˈzɪˈpoʊ
		chicken	ˈtʃɪkn̩	ˈtʰɪkn̩
	Glide	ribbon	ˈɹɪbn̩	ˈwɪbeɪ
		watches	ˈwɑːtʃəz	wɑːt
		whistle	ˈwɪsl̩	ˈwɪdɛ
2 syl Ss	Stop	popcorn	ˈpʰɑːpˌkʰɔɹn	ˈpʰɑːpˌkʰɔʊn
		bedroom	ˈbɛdˌɹũm	ˈbædˌwũm
		doghouse	ˈdɑːgˌhaʊs	ˈdɑːˈhoʊ
		downstairs	ˈdaʊ̃nˌstɛɹz (emphatic)	ˈdaʊ̃nˌdɛʊ
		cat food	ˈkʰæːtˌfuːd	ˈgæːdˈfuːd
		keychain	ˈkʰiːˌtʃeĩn	ˈgiːˌdɛ̃n
2 syl sS	Vowel	explodes	ˌ(ʔ)ɛksˈploʊdz	ˌɛʔˈpoʊd
	Stop	T.V.	ˌtʰiːˈviː	ˌtʰiːˈʋiː
	Fricative	shampoo	ʃæ̃ːmˈpʰuː	ˌs̪æ̃ːˈpʰuː
		thirteen	ˌθɚˈtʰĩːn	ˌʔʊˈtʰĩːn
	Glide	raccoons	ˌɹæːˈkʰũːnz	ˈwæːˌguː
2 syl wS	Vowel	again	(ʔ)əˈgɛ̃n	gɛ̃n
	Stop	balloon	bəˈlũːn	blũm
		balloons	bəˈlũːnz	lus
		canoe	kʰəˈnuː	kʰəˈnuː
		guitar	gɪˌtʰaɹ	gɪˌʎɑ
	Affricate	giraffe	dʒəˈɹæːf	sɪˈʎæːf
3 syl Sww	Vowel	animal	ˈ(ʔ)ænəml̩	ˈ(ʔ)ænəml̩

	Fricative	furniture	ˈfɝnətʃɚ	ˈfʊdɛʔ
		vegetable	ˈvɛdʒtəbl̩	ˈʔʌbɪdə
		skeleton	ˈskɛlətn̩	ˈsʌ.ɛ̃.ĩ
	Glide	hospital	ˈhɑːspɪɾl̩	ˈhɑːpɪdə
3 syl Sws	Stop	parachute	pʰæːɹəˌʃuːt	ˈbɛˌtuːk
		buttercup	ˈbʌɾɚˌkʰʌp	ˈbʌtˈkʰʌp
		dinosaur	ˈdaɪnəˌsɔɹ	ˈdaɪˌdə
	Fricative	spiderweb	ˈspaɪɾɚˌwɛb	ˈpaɪˈwɪb
	Lateral	living room	ˈlɪvĩŋˌɹuːm	ˈlɪˌwuː
3 syl Ssw	Stop	triangle	ˈtʰɹaɪˌæ̃ːŋgl̩	ˈlʌˌbɪˌbɪ
		grasshopper	ˈgɹæːsˌhɑːpɚ	ˈgæːˌhɑˈpĩn
	Nasal	marshmallow	ˈmaɹʃˌmɛloʊ	ˈmaːˌtoʊ
	Glide	hamburger	ˈhæ̃ːmˌbɝgɚ	ˈhæ̃ːmˌbʊgʊ
		rectangle	ˈɹɛkˌtæ̃ːŋgl̩	ˈwɑːˌtɪdɪ
	Vowel	October	ˌɑːkˈtʰoʊbɚ	ˈdoʊbə
		umbrella	ˌʌ̃mˈbɹɛlə	ˈʌˌbʌˌbʌ
	Nasal	November	ˌnoʊˈvɛ̃mbɚ	ˈnoʊˈvoʊ
	Fricative	fruit salad	ˌfɹuːt ˈsæːləd	ˈfuːt ˌsæːlɛ
		volcano	ˌvɑːlˈkʰeɪnoʊ	ˈfaˌdəˌdə
3 syl wSw	Vowel	electric	(ʔ)əˈlɛktɹɪk	ʌˈlɛtɪʔ
	Stop	banana	bənæːnə	ˈbiːˌnæˌna
		tomato	tʰəˈmeɪɾoʊ	ˈmɛ̃ndoʊdoʊ
		computer	kʰə̃mˈpʰjuɾɚ	gəˈpjutʰə
		gorilla	gəˈɹɪlə	gəˈɪ.ɪə
	Nasal	magician	məˈdʒɪʃn̩	mʌˈdɪʐə
		mosquito	məˈskiːɾoʊ	ˌməˈkeɪɾĩn
3 syl swS	Vowel	afternoon	ˌ(ʔ)æːfɾɚˈnũːn	ˌæːfəˈnũːn
	Stop	kangaroo	ˌkʰæ̃ːŋgəˈɹuː	ˌgʌˈkuː
	Nasal	magazine	ˌmæːgəˈzĩːn	ˈmæːzəˌzɪ

	Fricative	violin	ˌvaɪ.əˈlĩn	ˈfaɪˌlĩn
	Lateral	lemonade	ˌlɛməˈneɪd	ˌlɛˈmeɪ
4 syl Swsw	Vowel	alligator	ˈ(ʔ)æːləˌgeɪɾɚ	ˌɑːˈvɑːdĩn
	Glide	watermelon	ˈwɑːɾɚˌmɛln̩	ˈwɑːˌmaɟĩn
4 syl Swws	Glide	washing machine	ˈwɑːʃĩŋ məˈʃĩːn	ˈwɑːzĩ məˌtĩː
4 syl Ssww	Stop	cash register	ˈkʰæːʃˌɹɛdʒɪstɚ	ˈkʰɑːˌwɛˌɟa
4 syl swSw	Vowel	invitation	ˌ(ʔ)ĩnvəˈtʰeɪʃn̩	ˈɪʊɛˈʊɛ
4 syl wSww	Vowel	arithmetic	(ʔ)əˈɹɪθməˌtɪk	ʌˈt̪ʌˌmɛˌt̪ɪ
	Fricative	thermometer	θɚˈmɑːməɾɚ	ˌt̪əmɑːdəˌdɪs
4 syl wSsw	Stop	police station	pʰəˈliːs ˌsteɪʃn̩	ˈpʰiːˈdæːˌdɛ̃n
5 syl swSww	Glide	hippopotamus	ˌhɪpoʊˈpʰɑːɾəməs	ˌhɪˈpʰoʊˈpʰeɪʔɪ.ʌ
5 syl wsSww	Vowel	electricity	əˌlɛkˈtʰɹɪsɪɾi	ˈlʌˌdidi
5 syl wswSw	Stop	communication	kʰəˌmjũːnəˈkʰeɪʃn̩	ˌgʌˌmiˈgʰeɪ
6 syl Sws wSw	Fricative	video recorder	ˈvɪˌɾioʊ ɹiˌkʰɔɹɾɚ	ˈfɪtˌjoʊ ˌwiˌkʰət
Sww sww	Nasal	musical instrument	ˌmjuːzɪkl̩ ˈĩnstɹəmn̩t	ˈmjuːˌʔoʊˈĩnzdə