On the anatomy of a chain shift[1]

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Abstract

Phonological chain shifts have been the focus of many theoretical, developmental, and clinical concerns. This paper considers an overlooked property of the problem by focusing on the typological properties of the widely attested 's > θ > f' chain shift involving the processes of Labialization and Dentalization in early phonological development. Findings are reported from a cross-sectional study of 234 children (ages 3 years; 0 months–7;9) with functional (nonorganic) phonological delays. The results reveal some unexpected gaps in the predicted interactions of these processes and are brought to bear on the evaluation of recent optimality theoretic proposals for the characterization of phonological interactions. A developmental modification to the theory is proposed that has the desired effect of precluding certain early-stage grammars. The proposal is further evaluated against the facts of another widely cited developmental chain shift known as the 'puzzle > puddle > pickle' problem (Smith 1973).

1. Introduction

A common phenomenon in both first- and second-language acquisition and in fully-developed languages is for phonological processes to participate in a chain shift (e.g. Moreton & Smolensky 2002, Jesney 2005, Dinnsen 2008b). Chain shifts typically involve two phonological processes that interact in such a way that they result in an opaque generalization (i.e. one that is not surface-true). This phenomenon has generated much discussion and controversy in the theoretical, developmental, and clinical literature over the years and has raised questions about the very nature of chain shifts. A fresh look at chain shifts reveals some unexpected typological anomalies, the empirical underpinnings of which have not previously been recognized or reconciled. This paper begins to fill this gap by first establishing in Section 2 the facts associated with a commonly occurring chain shift attested in both typical and atypical phonological development. The finding that certain predicted interactions fail to be attested is then brought to bear on the evaluation of current optimality theoretic proposals for the characterization of interactions in Section 3. A possible solution to the problem is offered there which involves some developmental modifications to the theory. More specifically, it is suggested that both Optimality Theory with Candidate Chains (e.g. McCarthy 2007) and Comparative Markedness (e.g. McCarthy 2002) be modified in a particular way to preclude unattested early-stage grammars. The proposal is then evaluated

against the facts of another widely cited developmental chain shift known as the 'puzzle > puddle > pickle' problem (Smith 1973). The paper closes with a brief summary in Section 4.

The particular chain shift selected for consideration involves the processes of Labialization and Dentalization (e.g. Bernhardt & Stemberger 1998, Dinnsen & Barlow 1998). The Labialization process replaces target /θ/ with [f] (e.g. 'thumb' realized as [fʌm]), and Dentalization replaces target /s/ with [θ] (e.g. 'some' realized as [θʌm]). Either one of these processes might be contextually restricted or context-free. Importantly, interdentals derived from Dentalization do not undergo Labialization in the same context.

In rule-based theories of phonology (e.g. Kenstowicz 1994), chain shifts have been accounted for by extrinsically ordering two processes in a counter-feeding relationship. To achieve the results of the 's > θ > f' chain shift, Labialization must be ordered before Dentalization as shown in (1). At the point in the derivation where Labialization is considered for application, it is only target 'thumb' words that satisfy the structural description of the rule, thereby inducing the change of /θ/ to [f]. After Labialization has applied, Dentalization is then checked for its applicability and operates on target 'some' words, producing phonetic outputs that run counter to the generalization made by Labialization. The strict linear order imposed on these rules prevents the output of Dentalization from cycling back through to the Labialization process. The counterfeeding interaction between the two processes thus has the desired effect of producing phonetic outputs that are superficial exceptions to Labialization.

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(1) 's > θ > f' counterfeeding chain shift
Labialization: /θ/→[f]/...
Dentalization: /s/→[θ]/...
Underlying /sʌm/'some' /θʌm/'thumb' /fʌn/'fun'
Labialization — fʌm —
Dentalization θʌm — —
Phonetic [θʌm] [fʌm] [fʌn]
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As noted above, the status of chain shifts has been questioned on several fronts. For example, the theoretical characterization of chain shifts has proven especially challenging for recent constraint-based approaches to phonology, as evidenced by the various alternative proposals within Optimality Theory for handling such interactions (e.g. Prince & Smolensky 1993/2004; McCarthy 2002, 2007; Moreton & Smolensky 2002; Jesney 2007). From a developmental perspective, chain shifts have also been a focal point of debates on the relationship between perception and production, the learn-ability of opaque generalizations (especially when those generalizations are not evident in the target language), the source of overgeneralization errors, and the nature of children's underlying representations (e.g. Smith 1973, Macken 1980, Dinnsen, O'Connor & Gierut 2001, Dinnsen 2002, McCarthy 2002, Fikkert 2006, Vanderweide 2006, Ettlinger 2009, Tihonova 2009). Finally, on the clinical front, chain shifts have also been found to be especially resistant to treatment, often requiring extended and/or nonconventional treatment protocols (e.g. Dinnsen & Barlow 1998, Gierut & Champion 1999, Dinnsen 2008a, Morrisette & Gierut 2008). Despite all of the attention that chain shifts have been given, the hidden problem that seems to have been glossed over is whether or not the putative processes that constitute the 's > θ > f' chain shift and others are truly independent. That is, processes that are independent should each be free to occur (or not) in an individual phonology, and both processes should also be free to co-occur and interact in all logically possible ways across phonologies. The prediction is that the processes of the 's > θ > f' chain shift should exhibit the typological properties listed in

(2). However, to our knowledge, no developmental study has established the full set of typological facts for this pair of processes.

(2) *Predicted typological properties of the 's > θ > f' chain shift*
(a) Labialization occurs without Dentalization.
(b) Dentalization occurs without Labialization.
(c) Neither Labialization nor Dentalization occurs.
(d) Labialization and Dentalization co-occur and interact in all logically
possible ways (i.e. counterfeeding, feeding, and grandfather effect).

The predicted typology in (2) constitutes the empirical foundation upon which the 's > θ > f' chain shift is built. However, this typology has, to date, received only partial support (e.g. Bernhardt & Stemberger 1998, Dinnsen & Barlow 1998). That is, some evidence from individual case studies can be pulled together to instantiate (2a–c) and only one of the three logically possible types of interactions of (2d), namely the counterfeeding interaction that is the focus of this study. It is difficult to know from the available findings whether the lack of support for the other logically possible interactions associated with these processes is systematic or accidental. On the one hand, the gap could simply be due to the fact that no study has yet intended to investigate the larger typology. Alternatively, the lacuna could represent systematic peculiarities associated with the particular processes of this chain shift, which might help to explain how and why chain shifts have been so controversial. The prior findings associated with this chain shift are also difficult to interpret because methods and procedures in individual case studies often differ. In any event, the absence of compelling evidence instantiating the full typology can undermine arguments that depend on the validity of a putative chain shift. It is thus important to establish the facts surrounding this chain shift by employing a uniform set of procedures with a relatively large number of children and to determine the extent to which each predicted instance of the typology is attested.

The need to establish the facts relating to the occurrence/nonoccurrence of individual error patterns, as in (2a–c), would seem to be a straightforward matter. The more involved (and more interesting) problem is establishing the facts relating to the co-occurrence and interaction of error patterns, as in (2d). Naturally, the existence of any chain shift serves to document one of the logically possible types of interactions, namely a counterfeeding interaction, as exemplified in (1). There are, however, two other logically possible interaction types that are also predicted to occur. One of those logical possibilities is a feeding interaction. In rule-based derivational terms, such an interaction comes about from the first of two processes actively creating a representation to which the second process would apply. Returning to the two processes of Labialization and Dentalization, as set forth in (1), it should be possible to achieve a feeding interaction by reversing the order of the processes; Dentalization ordered before Labialization. The prediction would be that underlying /θ/ and those derived by Dentalization would both serve as inputs to Labialization, merging the distinction between /s/, /θ/, and /f/, in favor of [f], as illustrated in (3). Feeding interactions of this sort would be achieved straightforwardly in optimality theoretic terms by simply ranking the markedness constraints that ban coronal fricatives over antagonistic faithfulness constraints. This assumes, of course, a highly ranked faithfulness constraint demanding that corresponding segments maintain identity in the feature [continuant].

(3) *Predicted feeding interaction*
Underlying /sʌm/ 'some' /θʌm/ 'thumb' /fʌn/ 'fun'
Dentalization θʌm — —

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Labialization  fʌm  fʌm  —
Phonetic       [fʌm] [fʌm] [fʌn]
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The third logically possible type of interaction for processes associated with a chain shift has been referred to as a 'grandfather effect' in optimality theoretic terms (McCarthy 2002) and as 'nonderived environment blocking' (NDEB) in rule-based terms (e.g. Kiparsky 1982, Kenstowicz 1994). It is important to recognize grandfather effects as one of the logically possible interaction types for these processes because they share certain properties of both counterfeeding and feeding interactions. Clearly, however, something more than rule ordering would also be involved in derivational frameworks. Grandfather effects result in an opaque generalization (similar to counter-feeding interactions), but Dentalization must be ordered before Labialization (as in the feeding relation in (3)). The distinguishing characteristic of a grandfather effect relates to a well-supported principle of Lexical Phonology (e.g. Kiparsky 1982), which maintains that certain types of rules apply exclusively to derived representations. This means that Labialization would be expected to operate on the output derived from Dentalization, but it would be blocked from operating on an otherwise identical underlying /θ/ because that segment would not have been derived from some other process. Just as with counterfeeding interactions, there would be some superficial exceptions to Labialization, but the exceptions would come from a complementary class of words, namely target 'thumb' words.

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(4) Predicted grandfather effect
Underlying    /sʌm/'some'  /θʌm/'thumb'  /fʌn/'fun'
Dentalization θʌm  —  —
Labialization fʌm  NDEB  —
Phonetic      [fʌm] [θʌm] [fʌn]
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The characterization of grandfather effects in Optimality Theory has been problematic, engendering alternative proposals such as Comparative Markedness (e.g. McCarthy 2002) and the local conjunction of markedness with faithfulness constraints (e.g. Łubowicz 2002). As we will see, either of these proposals would need to be constrained to account for the developmental anomaly to be documented in this paper, and we will offer a possible modification on this front.

While feeding interactions, counterfeeding interactions, and grandfather effects have each been shown to occur for different pairs of error patterns in children's early phonological development (e.g. Dinnsen 2008b and references therein), it has not yet been established, one way or the other, that those same pairs of error patterns participate in any of the other logically possible interactions. This is an empirical anomaly that needs to be fleshed out if we are to gain a perspective on the 's > θ > f' chain shift and the controversies it has engendered. Accordingly, this paper will attempt to evaluate the independence of the processes associated with the 's > θ > f' chain shift by establishing the facts regarding the occurrence, nonoccurrence, and co-occurrence of Labialization and Dentalization through a large-scale cross-sectional study involving young children with phonological delays.

2. Cross-sectional study

2.1 Participants and general methods

The children who participated in this study were typically developing in all respects, except for evidence of a phonological delay. They scored within normal limits on all standardized tests of hearing, nonverbal intelligence, oral–motor structure and function, receptive vocabulary, and expressive and receptive language (for details, see Gierut 2008). However,

all children also scored at or below the 5th percentile on the *Goldman–Fristoe Test of Articulation* (Goldman & Fristoe 1986). This means that 95% of other children of the same age and gender as these participants had phonological systems that were more in keeping with the target phonology. Children with phonological delays were selected for study because they can offer a special window onto early phonological development. That is, the phonologies of children with phonological delays tend to resemble those of younger children with typical phonological development. However, many of the research challenges that arise in working with younger children are avoided with older children (Ferguson & Farwell 1975). For example, because younger children have shorter attention spans and limited understanding of structured elicitation tasks, it is often difficult to secure the type and amount of data needed to motivate phonological claims; older children with phonological delays do not present this same problem.

The data were drawn from the Developmental Phonology Archive of the Learnability Project at Indiana University (Gierut 2008). The Archive includes an exhaustive compilation of data on the productive phonological development of 234 children. Moreover, the data were collected in a systematic, uniform manner, facilitating comparisons within and across children and over time. Only the pre-treatment phonologies of these children were considered in this study. All claims about the children's phonologies were based on a comprehensive speech sample and standard phonological analysis procedures (Gierut 2008). The speech sample for each child was elicited in a spontaneous picture-naming task and was audio recorded. The pictures related to a probe list of 544 words familiar to children of that age (Gilhooly & Logie 1980a, b; Bird, Franklin & Howard 2001), which sampled the full range of English consonants in initial, medial, and final positions in multiple exemplars. The audio-recorded sessions were phonetically transcribed on the basis of impressionistic judgments by trained listeners with considerable experience in the transcription of clinical populations. For transcription reliability purposes, 10% of all probes were retranscribed by an independent judge. The overall transcription reliability measure was 92% agreement for all phonologies, which is within the range of what is typically deemed acceptable (e.g. Shriberg & Lof 1991).

2.2 Analysis procedures

The pretreatment phonological records of all 234 children in the Archive were examined to determine the extent to which the typology in (2) was instantiated. For the purposes of our analysis, the larger probe list of 544 words made available a minimum of 17 words that sampled each of the target fricatives /f/ and /s/ and 15 words that sampled the target fricative /θ/ for a combined total of no less than 49 words per child. To evaluate the predictions of the typology, at the very least, all children had to have /f/ in their phonemic inventories in order to be considered. The reason behind this condition was that /f/ was a potential product of Labialization, a feeding interaction, or a grandfather effect. This had the consequence of setting aside those children whose pretreatment inventories included both /s/ and /θ/ but not /f/ (n = 6) and those children whose sole fricative phoneme was /s/ or /θ/ (n = 27). These latter cases would have no probative value in judging the independence of the two processes. It should also be clear that these criteria required us to set aside children who did not have any fricatives in their pretreatment phonemic inventories (n = 41). Such cases would only trivially comply with the typological option in (2c) of No Labialization and No Dentalization. For any of these phonemes to be judged as occurring in the inventory, it had to occur with an accuracy at or above 20% and/or in at least two minimal pairs. The combined effect of these various criteria set aside 74 of the 234 children from consideration. The remaining 160 children's phonologies allowed for nontrivial comparisons and were thus entered into the larger analysis.

In addition to the above criterion for establishing the phonemic use of relevant sounds, it was also necessary to set up an independent criterion for identifying when the substitution process of Labialization or Dentalization was active in a child's phonology. We adopted the operational definition that active processes were those that affected a minimum of 25% of relevant words with a specific substitution pattern (e.g. McReynolds & Elbert 1981). However, as we will show, the actual percentage of words affected by active processes was, on average, considerably higher. One reason for accepting a value as low as 25% is that it would be generous in identifying an interaction, if it were to occur. This is important because, as we will show, even this generous criterion failed to identify certain predicted interactions. There is also some value in not accepting a lower criterion level because so few words would be affected (i.e. four or fewer words), making it difficult to differentiate random errors from those that are systematic. To further clarify the implementation of this criterion, if target /s/ were produced as [θ] in 25% or more of the relevant words, Dentalization was considered active. However, other substitutes for target /s/, such as a stop, [h], or a [s̠] (i.e. a distortion of the target phoneme), were not counted as evidence of Dentalization. The particular distinction between [θ] and [s̠] was based on an impressionistic judgment by trained transcribers ; acoustic analyses would not have been possible, especially given the limited number of tokens. Any resultant misclassification of these sounds would only impact our calculation of the number of cases exhibiting Dentalization, but it would not impact the larger typology. The rationale for excluding these alternative substitution patterns is that their outputs could not interact with Labialization in any of the ways relevant to the evaluation of the typology in (2). The same strict criterion was applied to Labialization. That is, the target coronal fricative /θ/ had to be realized as the labial fricative [f] to count as an instance of Labialization.

To establish a counterfeeding interaction between Labialization and Dentalization, it was necessary for the two processes to co-occur in a given phonology with each process meeting the minimum 25% occurrence criterion. To identify a feeding interaction or a grandfather effect, certain inferences were necessary because the output of Dentalization would immediately be subject to Labialization, resulting in [f] as the observed output. Consequently, it was assumed that Dentalization and Labialization were both active if at least 25% of the target /s/ words were realized with [f] as the substitute. This latter assumption is necessary within rule-based derivational accounts because the output of Dentalization must be hypothesized as an intermediate step in a derivation and would, thus, not be directly observable in a putative feeding interaction or a grandfather effect. While this assumption might seem overly generous, we will show that it did not skew the results in favor of feeding interactions or grandfather effects when there were none. No special inferences about the activity of these processes would be required in optimality theoretic accounts because the evaluation of output candidates is conducted in parallel.

To ensure a measure of analysis reliability, 11% (n = 18) of the 160 children's data sets were reanalyzed by an independent judge to confirm the presence/absence of Labialization and/or Dentalization in accord with the 25% occurrence criterion. There was 100% agreement between the original analyses and the reanalyses.

2.3 Results

The results of our analyses are first reported separately for each of the typological predictions from (2) and are then followed by a summary of the overall group results. As noted earlier, processes that were judged to be active according to the 25% occurrence criterion affected on average a much higher percentage of relevant words. More specifically, active Dentalization processes were found to affect on average 59% of relevant words (range 29%–100%, median 59%). Active Labialization processes were found to affect on average 64% of relevant words (range 26%–100%, median 67%). In general, any remaining words

not affected by Dentalization or Labialization were produced in error by other processes not relevant to the typology.

2.3.1 Labialization without Dentalization—From the set of 160 relevant phonologies, our analyses revealed that 94 children (59% of the sample) exhibited Labialization without Dentalization. The mean age of these children was 4 years; 5 months. All children in this group included /f/ in their phonemic inventories, and they may or may not have produced target /θ/ and/or /s/ correctly in some words. Importantly, target /θ/ was replaced by [f] in at least 25% of the relevant words. Equally important, Dentalization was not active, meaning that target /s/ was not replaced by [θ] in 25% of the relevant words. The data in (5), from Child 153 (age 5;8), illustrate the essentials of this case and are representative of the other children who constituted this subgroup.

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(5) Child 153 (age 5;8): Labialization without Dentalization
(a) /θ/ replaced by [f] (Labialization)
fʌndoʊ 'thunder' maʊf 'mouth'
fʌm 'thumb' tuf 'tooth'
(b) /s/ not replaced by [θ] (No Dentalization)
bʌs 'bus' soʊp 'soap'
dʒusi 'juicy' sʌn 'sun'
(c) /f/ produced target-appropriately
feɪs 'face' wuf 'roof'
kɔːfɪŋ 'coughing' lif 'leaf'
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2.3.2 Dentalization without Labialization—In complement to the above group of children, three children (2% of the sample) exhibited Dentalization without Labialization. The mean age of these children was 4;2. These children produced /f/ and /θ/ correctly, but replaced /s/ with [θ]. The data in (6), from Child 124 (age 3;1), illustrate the solitary activity of Dentalization and are representative of the other cases in this subgroup.

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(6) Child 124 (age 3;1): Dentalization without Labialization
(a) /s/ replaced by [θ] (Dentalization)
beɪθbɔl 'baseball' maʊθ 'mouse'
θoʊp 'soap' bʌθ 'bus'
(b) /θ/ produced target-appropriately (No Labialization)
bæθ 'bath' θif 'thief'
maʊθ 'mouth' tuθi 'toothy'
(c) /f/ produced target-appropriately
kɔf 'cough' hæfin 'laughing'
wuf 'roof' gufi 'goofy'
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2.3.3 No Labialization and No Dentalization—A third group of 52 children (32% of the sample) produced target /f/ correctly and may or may not have produced target /θ/ and/ or /s/ correctly. The mean age of these children was 4;7. Importantly, these children did not substitute [f] or [θ] for any of the fricatives. See (9) in Section 2.3.5 below for alternative realizations of these coronal fricatives. The data in (7), from Child 221 (age 5;6), are representative of the other cases in this subgroup of No Labialization and No Dentalization.

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(7) Child 221 (age 5;6): No Labialization and no Dentalization
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(a) /s/ not replaced by [θ] (No Dentalization)
sænta 'santa' ʤus 'juice'
soʊp 'soap' dusi 'juicy'
(b) /θ/ produced target-appropriately (No Labialization)
θʊsti 'thirsty' tiθ 'teeth'
bæθ 'bath' tiθi 'teethy'
(c) /f/ produced target-appropriately
faɪv 'five' wif 'leaf'
tɔfɪŋ 'coughing' faɪjʊ 'fire'
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The above results replicate findings from other studies (e.g. Bernhardt & Stemberger 1998) and attest to the independence of Labialization and Dentalization in terms of the simple occurrence/nonoccurrence of each error pattern. However, these results say nothing about the potential interaction of those error patterns. The assessment of an interaction depends on the co-occurrence of error patterns. The results that follow bear on the typology of potential interactions.

2.3.4 Counterfeeding interaction—Eleven children (mean age 4;1) exhibited the co-occurrence of Labialization and Dentalization in a standard counterfeeding interaction (7%). All of these children produced target /f/ correctly. Target /θ/ was replaced by [f] (Labialization), and target /s/ was replaced by [θ] (Dentalization). Importantly, the product of Dentalization did not undergo Labialization, resulting in superficial exceptions to Labialization. The data in (8), from Child 131 (age 4;8), are representative of the other children assigned to this subgroup.

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(8) Child 131 (age 4;8): Counterfeeding chain shift
(a) /s/ replaced by [θ] (Dentalization)
bʌθ 'bus' maʊθ 'mouse'
aɪθi 'icy' beɪθbɔ 'baseball'
(b) /θ/ replaced by [f] (Labialization)
maʊf 'mouth' fʌndʊ 'thunder'
fʌm 'thumb' tuf 'tooth'
(c) /f/ produced target-appropriately
kɔf 'cough' wæfin 'laughing'
faɪɤ 'five' faɪjʊ 'fire'
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2.3.5 Feeding interaction—Interestingly, no children were found to exhibit the predicted feeding interaction between these two processes. This means that no child produced [f] as the substitute for both /θ/ and /s/. This is surprising on several counts. First, it would seem that there was ample opportunity to witness a feeding interaction, if one were to occur, given that 29 of the 160 children, independent of their classification in this study, failed to meet the minimum criterion for establishing the phonemic status of any target coronal fricative. Stated differently, /f/ was the sole fricative that achieved phonemic status for these children.

These 29 children raise questions about what might have happened to the coronal fricatives, given that they were not all realized as [f]. The table in (9) summarizes the results from these 29 children by reporting the number of children who employed each of several different substitution patterns for specific target coronal fricatives.

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(9) Coronal fricative substitution patterns
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Target /θ/	# occurrence	Target /s/	# occurrence
Stopping	6	Stopping	13
Variable	7	Variable	7
Labialization	16	Dentalization	4
		Distortion	5

Stopping was the most common, unified strategy that these children employed for avoiding coronal fricatives. Such a process would effectively bleed Labialization and Dentalization, rendering those processes inert or inactive. Some children employed one strategy for target /s/ (e.g. Stopping) and a different strategy for target /θ/ (e.g. Labialization). The end result of any two strategies was the exclusion of all coronal fricatives. Some of the other coronal fricative substitution patterns evidenced by these 29 children are more difficult to classify owing to their incidental or nonsystematic character. We have, thus, grouped Deletion and Glottal Replacement under the general category 'Variable' and Lateralization, Affrication, or Lisping under the broad category 'Distortion'. The Appendix provides representative cases from different children illustrating some of the main strategies for dealing with coronal fricatives.

Finally, the nonoccurrence of feeding interactions is unexpected because such interactions are presumably unmarked, result in surface-true generalizations, and are thought to be reflective of the initial state (e.g. Smolensky 1996).

To be clear, it should have been possible to differentiate feeding interactions, if they had occurred, from the cases in Section 2.3.3 above of No Labialization and No Dentalization in one important respect. In the cases of a feeding interaction, the fricative [f] should have been the substitute for both target /s/ and /θ/ in at least 25% of the relevant words. In the cases of No Labialization and No Dentalization, [f] would not be the substitute for either of the other target fricatives. We will return to this anomaly in the Discussion.

2.3.6 Grandfather effect—Surprisingly, for this instance of the typology as well, the predicted grandfather effect was not observed in the phonology of any of the 160 children. That is, there were no children who produced target /θ/ correctly while also replacing target /s/ with [f]. This is unexpected because grandfather effects have been documented for developing phonologies (e.g. Dinnsen 2008b and references therein), and because they are quite common and well documented in fully developed languages (e.g. Kiparsky 1982, McCarthy 2002). This anomaly is also considered further in the Discussion.

2.3.7 Summary of results—The results from this study are summarized in Figure 1. Out of the set of 160 children who were relevant to the evaluation of the typological predictions in (2), the prediction that was instantiated most often was the case of Labialization without Dentalization. The second most common case involved the absence of both Labialization and Dentalization. The case of Dentalization without Labialization was the least commonly instantiated prediction. The prevalence of Dentalization was probably underestimated due to the very strict criterion that we imposed, namely that Dentalization had to result specifically in [θ] and not in a distorted /s/ (i.e. [s̪]) to be considered active. The most interesting finding was that, when Labialization and No Labialization/No Dentalization, 32% Labialization and Dentalization co-occurred, they always and only interacted in a counter-feeding chain shift. The predicted feeding interaction and grandfather effect were not attested in the study population.

The typological predictions concerning the independence of Labialization and Dentalization in (2) were only partially supported by the findings of this study. On the one hand, it was firmly established by 93% of the cases that each process could occur without the other or not

at all (e.g. (2a–c)). However, the predictions relating to the interaction of these processes failed to be supported in important respects (e.g. (2d)). In particular, while the predicted counterfeeding interaction was attested, feeding interactions and grandfather effects were not observed. These results raise new questions to be discussed in the next section regarding the theoretical characterization of interacting error patterns and the nature of the 's > θ > f' chain shift and its relation to other putative chain shifts.

3. Discussion

The main question that arises from our results is: Why was a counterfeeding interaction between Labialization and Dentalization observed, but not a feeding interaction or a grandfather effect? There are several possible approaches to answering this question. We first take up the possibility that the gap could be accidental and then consider the theoretical consequences of the alternative, namely that the gap is indeed systematic. In the course of considering this latter option, we sketch a possible solution to the problem and then relate the solution to problems associated with another well documented developmental chain shift.

3.1 Accidental gap

It might be argued that we failed to observe a feeding interaction and a grandfather effect because we tapped into the children's phonologies either too early or too late and simply missed the stages of development when these interactions might have occurred. Such an approach to the question suggests that the nonoccurrence of these interactions in this study was an accidental gap that might be remedied by additional empirical research.

Along these lines, it might be fruitful in a future study to track the longitudinal development of children who present with phonemic inventories that exclude all fricatives. The 41 children from the larger sample of 234 who presented with no fricatives in their pretreatment phonologies would be good candidates for such an investigation. The point would be to watch for the subsequent suppression of Deletion or Stopping and/or the emergence of /f/ in the inventory, which might serve as the substitute for target /s/. This might reveal one of the missing interaction types. Hypothetically, if one of those previously unattested interactions were to occur, it seems likely that the feeding interaction would occur relatively early in development given its presumed unmarkedness and the larger number of words predicted to be produced in error. Insofar as grandfather effects are predicted to yield some target-appropriate productions, we might further expect that such interactions would be more evident in later stages of development, possibly just prior to achieving the end-state grammar. These possibilities must remain open questions awaiting a corresponding longitudinal investigation.

3.2 Systematic gap

The other approach to the question of the nonoccurrence of a feeding interaction and a grandfather effect associated with Labialization and Dentalization is that the gap is systematic and in need of a theoretical explanation. It is important in this regard to note that the feeding interaction and the grandfather effect would have exhibited a commonality that was not shared by the attested counterfeeding interaction. That is, independent of whether Dentalization and Labialization were to participate in a feeding interaction or a grandfather effect, the prediction is that they both would result in the substitution of /s/ with [f]. The attested counterfeeding interaction between these two processes never resulted in the substitution of /s/ with [f]. The Dentalization part of the chain shift tolerated the substitution of /s/ with [θ], which involved a manner change from a grooved fricative to a nongrooved fricative (e.g. Ladefoged & Maddieson 1996). Grooved sounds are sometimes equated with

the feature [+ strident] (e.g. Chomsky & Halle 1968). The Labialization part of the chain shift tolerated the substitution of [f] for /θ/, which involved a change in the [coronal] place feature. What seems not to have been tolerated was a change in both the place and manner features in the same segment. The generalization appears to be that these two processes can co-occur if and only if they apply minimally, as would follow from a counterfeeding interaction.

The fact that some processes might apply minimally is not in itself a new observation. For example, similar cases involving the minimal application of other interacting processes have been identified in young children's developing phonologies and in fully developed languages (e.g. Farris-Trimble 2008). However, the cases considered by Farris-Trimble differ from chain shifts in that they generally involved an additional process that intervened to induce an alternative repair, such as deletion. However, deletion was apparently not an available option for the 11 children in our study who exhibited a counterfeeding interaction, given that they produced some sound as a correspondent of the target fricatives. Interestingly, for those 94 children in the current study who exhibited Labialization without Dentalization, it could be argued in many cases that Dentalization was blocked from feeding Labialization by some other intervening process such as Deletion or Stopping. Such a change alone would have been sufficient to remove /s/ from the domain of Dentalization. In those cases, a change in the [continuant] feature or the deletion of the entire segment would have been preferred over a change that would have led to the multiple feature changes entailed in a feeding interaction. Stopping or Deletion would effectively render Dentalization inactive for those children who exhibited Labialization without Dentalization. Neither Stopping nor Deletion was, however, an available repair for those children who evidenced the chain shift because all target fricatives were at least realized as a fricative.

The larger theoretical problem posed by the apparent need for some processes to apply minimally is that there does not seem to be an available theoretical mechanism that can also prevent the multiple feature changes that would follow from a feeding interaction or a grandfather effect. For example, the approach adopted by Farris-Trimble (2008) to ensure the minimal application of interacting processes was to invoke weighted constraints in terms of Harmonic Grammar (e.g. Smolensky & Legendre 2006). While Harmonic Grammar can achieve minimal application effects of the sort noted by Farris-Trimble, the framework was also set up to provide for multiple feature changes within a segment, as would follow from a feeding interaction. Thus, it appears that Harmonic Grammar cannot (and would not want to) provide for the principled exclusion of the unattested feeding interaction of Dentalization and Labialization. Harmonic Grammar, as currently conceived, has the further problem of not being able to achieve the specific minimal application effects associated with chain shifts (cf. Albright, Magri & Michaels 2008). The same problems of predicting the occurrence of interactions that appear to be unattested, while also accounting for attested interactions that are opaque, challenge other contemporary optimality theoretic proposals. These problems implicate classic Optimality Theory (e.g. Prince & Smolensky 1993/2004), Local Constraint Conjunction (e.g. Smolensky 1995, Moreton & Smolensky 2002), Comparative Markedness (e.g. McCarthy 2002), and Optimality Theory with Candidate Chains, or OT-CC (e.g. McCarthy 2007). Theories of phonology have never before been confronted with the need to prevent, in principle, some processes from participating in a feeding interaction. Such interactions have always been viewed as preferred, unmarked phenomena that yield perfectly transparent generalizations (e.g. Kiparsky 1965, Donegan & Stampe 1979, Prince & Smolensky 1993/2004, Kenstowicz 1994). Independent of the apparent need to prevent some feeding interactions, some current theories have also had to invoke special machinery to provide for the minimal application effects associated with chain shifts (e.g. McCarthy 2002, 2007; and references therein).

The findings from this study and the associated theoretical problems suggest, at the very least, that current theories are in need of revision. It is obviously beyond the scope of this paper to solve this larger theoretical problem, but one promising possibility for part of the problem does suggest itself from the insights and architectural elements of Optimality Theory with Candidate Chains (McCarthy 2007). As noted above, this particular framework provides for both feeding interactions and counterfeeding interactions (among others), but in doing so, it also has a built-in mechanism for disallowing particular feeding interactions. With a slight modification to the theory, it may be possible to provide for the principled exclusion of a feeding interaction when particular processes are involved. To see how this might work, first consider that one of the innovations of McCarthy's proposal for the characterization of opacity effects was the introduction of a new way of conceiving of output candidates, namely 'candidate chains', along with a new family of constraints, namely 'Precedence constraints'. In this framework, each input has a small, finite set of competing output candidates with each reflecting a highly restricted chain of unfaithful mappings from the fully faithful candidate. For example, in the case of the 's > θ > f' chain shift, the valid chains for an input /s/ would be limited to those schematized in (10), assuming the highly ranked faithfulness constraint ID[continuant], which demands identity between corresponding segments in terms of the feature [continuant].

```
(10)  Valid candidate chains for input /s/
(a) [s]
(b) [s] >[θ]
(c) [s] >[θ] >[f]
```

Candidate (10a) represents the fully faithful candidate. Candidate (10b) reflects a departure from the fully faithful candidate compelled by a markedness constraint banning grooved coronal fricatives (i.e. *s). This unfaithful mapping entails a single harmonically improving violation of the constraint ID[grooved], which demands that corresponding segments be identical in terms of the feature [grooved]. Candidate (10b) is also the intended winner in a counterfeeding interaction of these processes. Candidate (10c) builds on candidate (10b) by adding a subsequent ID[coronal] violation compelled by a markedness constraint banning interdentals (i.e. *θ). Candidate (10c) would represent the result of a feeding interaction. This is where Precedence (P_REC) constraints come into play. Such constraints assess violations to a chain depending on the internal order of its faithfulness violations. For example, the P_REC constraint in (11) would assign two violations to candidate (10c) and only one violation to candidate (10b).

```
(11)  Precedence constraint
P_REC(ID[coronal], ID[grooved]): Every violation of ID[grooved] must
be preceded by a violation of ID[coronal], and it must not be followed
by a violation of ID[coronal].
```

The definition of P_REC includes two clauses, either or both of which can assign a violation to a candidate chain. The reason candidate (10c) incurs two violations of P_REC is, first, because the ID[grooved] violation was not preceded by a mandatory ID[coronal] violation, and, second, because the ID[grooved] violation was followed by a prohibited ID[coronal] violation. Candidate (10b) is preferred over (10c) because, while (10b) does incur one violation of P_REC for its failure to include an ID[coronal] violation before its ID[grooved] violation, it at least complies with the second clause of P_REC for not having a following violation of ID[coronal]. If this P_REC constraint were ranked high enough in the hierarchy

(e.g. above the markedness constraint banning interdental fricatives (i.e. *θ), but below the markedness constraint banning grooved coronal fricatives (i.e. *s)), it would eliminate the feeding candidate (10c) in favor of the counterfeeding candidate (10b). The required ranking is given in (12) along with generic tableaux for an input /s/ and /θ/. This account corresponds with other accounts of chain shifts within OT-CC.

(12) *Chain shift*
*s ≫ ID[grooved], ID[continuant] ≫ P_{REC}(ID[coronal], ID[grooved]) ≫
*θ ≫ ID[coronal]

/s/	*s	ID[grvd]	ID[cont]	PREC (ID[cor],ID[grvd])	*θ	ID[cor]
(a) s	*!					
(b) ☞ s > θ		*		*	*	
(c) s > θ > f		*		**!		*
/θ/						
(a) θ					*!	
(b) ☞ θ > f						*

As currently conceived, OT-CC would also erroneously predict a feeding interaction if the hierarchy were essentially the same in all respects, except that the two markedness constraints against coronal fricatives (i.e. *s and *θ) were ranked above P_{REC}(ID[coronal], ID[grooved]), as might follow from the default ranking of markedness over faithfulness in early stages of acquisition (e.g. Smolensky 1996). That is, the greater demand to comply with the two undominated markedness constraints and ID[continuant] would override any violations assessed by this particular P_{REC} constraint and result in all fricatives being realized as [f]. The unattested feeding interaction could, however, be circumvented if ID[continuant] were forced to be ranked lower in the hierarchy under certain circumstances. Our suggested modification to the theory takes advantage of the observation that one of the preferred strategies for avoiding target coronal fricatives seems to be to employ Stopping (see especially (9) in Section 2.3.5 above and the Appendix for illustrative cases). This suggests that the faithfulness constraint ID[continuant] must be ranked lower in the hierarchy to achieve this effect, as might be expected with crucially ranked faithfulness constraints that are engaged in a conspiracy (e.g. Kisseberth 1970, Prince & Smolensky 1993/2004). The putative conspiracy in this instance would be the plan to avoid target coronal fricatives. Consequently, the modification to OT-CC that is called for here is to impose an initial-state (default) fixed ranking of ID[continuant] below P_{REC}(ID[coronal], ID[grooved]). This would have the desired consequence of precluding a feeding interaction when the markedness constraints against coronal fricatives are undominated. The hierarchy and tableaux in (13) illustrate the Stopping option for coronal fricatives. The candidate chains in this instance differ from those in (10) and (12) because all valid chains are determined by the constraint hierarchy. Note, for example, that for an input /s/, the chain s > θ would not be a valid chain because it is not harmonically improving according to the hierarchy in (13) and is, thus, excluded from consideration.

(13) *Coronal Stopping*
*θ, *s ≫ ID[grooved] ≫ P_{REC}(ID[coronal], ID[grooved]), ID[coronal] ≫
ID[continuant]

	/s/	*θ	*s	ID[grvd]	PREC (ID[cor], ID[grvd])	ID[cor]	ID[cont]
(a)	s		*!				
(b) ☞	s > t			*	*		*
(c)	s > f			*	*	*!	
	/θ/						
(a)	θ	*!					
(b) ☞	θ > t						*
(c)	θ > f					*!	

We further propose that the fixed-ranking requirement between P_REC(ID[coronal], ID[grooved]) and ID[continuant] is suspended once one of the markedness constraints against coronal fricatives has been demoted below P_REC(ID[coronal], ID[grooved]). This means that ID[continuant] and P_REC(ID[coronal], ID[grooved]) become freely permutable after some learning has taken place regarding coronal fricatives. The ranking in (12) for a chain shift reflects some imperfect (partial) learning about coronal fricatives and is one possible permutation of P_REC(ID[coronal], ID[grooved]) and ID[continuant] that would follow from relaxation of the fixed ranking of these constraints. The learning is considered imperfect because, while it does not result in any correct realizations of coronal fricatives, it does at least yield a fricative for a target fricative, and it introduces a distinction in the behavior of coronal fricatives that begins to approximate the target distinction. This might reasonably follow from a child's recognition (i) that target fricatives are not stops and must instead have fricative correspondents in the output, and (ii) that there is some further difference between target coronal fricatives that must also be maintained (albeit incorrectly) in the child's output. Current error-driven learning algorithms (e.g. Tesar & Smolensky 1998) do not yet provide for imperfect learning of this sort, but see Tihonova (2009) for a promising alternative. Finally, the progression from the chain shift stage to full faithfulness would require the demotion of *s immediately below ID[grooved] along with the demotion of *θ below ID[coronal]. Error-driven learning of this sort might reasonably follow in one or more steps from the child's recognition that specifically /θ/ and /f/ contrast and further that /s/ and /θ/ contrast.

This part of the solution that we are advancing here is clearly an early preliminary step. There are as yet a number of unresolved issues that confront OT-CC generally, including, for example, whether there is a default ranking of P_REC constraints and whether there are limits on the constraints that participate in P_REC relations. Additionally, OT-CC makes no claims one way or the other about the characterization of grandfather effects. Specific proposals for the characterization of such effects, namely the local conjunction of markedness with faithfulness (e.g. Łubowicz 2002) or Comparative Markedness (e.g. McCarthy 2002), are relevant here and would also need to be constrained to exclude a grandfather effect for these processes. Consider, for example, that the particular innovation of Comparative Markedness was to split each conventional markedness constraint into one that bans a marked structure that is shared with the fully faithful candidate ($_oM$) and another that bans the same marked structure when not shared with the fully faithful candidate ($_nM$). The different permutations of these constraints relative to a faithfulness constraint provide for feeding interactions, counter-feeding interactions, grandfather effects, and full faithfulness. Our suggestion would be to simply remove the markedness constraint *θ from the domain of comparative markedness because it might never need to be analyzable into the comparative markedness counterparts $_o*θ$ and $_n*θ$. A return to standard conceptions of markedness, at least for this particular markedness constraint, would effectively preclude the possibility of a grandfather effect involving interdental fricatives, and it would leave the characterization of the attested counterfeeding interaction and the principled exclusion of the feeding interaction to OT-CC. Clearly, much more research is called for that attempts to identify processes that can and cannot interact in this way. Nevertheless, an interesting test case of our proposal is provided by the classic developmental chain shift known as the

'puzzle > puddle > pickle' problem first described by Smith (1973), which is reconsidered below.

3.3 The 'puzzle > puddle > pickle' problem

The anomalous behavior of the 's > θ > f' chain shift may not be an isolated phenomenon. Similar developmental asymmetries can be found in Amahl's widely cited 'puzzle > puddle > pickle' problem (Smith 1973). As the problem was originally described, it involved two presumably independent, interacting processes, namely Velarization and Stopping. The Velarization process changed a coronal stop to a velar before the liquid consonant /l/, e.g. 'puddle' words were realized as [pʌgl]. 'Pickle' words conformed to the requirements of Velarization and remained unchanged. Velarization essentially merged the consonantal place distinction between 'puddle' and 'pickle' words. The Stopping process replaced fricatives with a stop, e.g. target 'puzzle' words were realized as [pʌdl]. Importantly, these processes interacted with one another such that 'puddle' words derived from Stopping were blocked from undergoing Velarization ; at the same time, target 'puddle' words did undergo Velarization. This blocking effect was achieved by ordering Velarization before Stopping in a counterfeeding relation, resulting in a chain shift similar to that of the 's > θ > f' chain shift. The derivation in (14) illustrates this counterfeeding interaction.

```
(14) Attested counterfeeding interaction (Smith 1973)
Underlying /pʌzl/'puzzle'  /pʌdl/'puddle'  /pɪkl/'pickle'
Velarization —              pʌgl            —
Stopping     pʌdl           —               —
Phonetic     [pʌdl]         [pʌgl]          [pɪkl]
```

We are not aware of any developmental studies showing that Amahl or any other child exhibited a feeding interaction or a grandfather effect involving these two processes. If a feeding interaction between these two processes were to occur, the output of Stopping would serve as the input to Velarization, merging the manner and place distinction in favor of 'pickle' words. If a grandfather effect were to occur, target 'puddle' words would be produced correctly, but 'puzzle' words would undergo both Stopping and Velarization, being produced as 'pickle' words. The apparently unattested substitution pattern that would be common to a feeding interaction and a grandfather effect for these two processes would be the replacement of a fricative with a velar stop before the liquid consonant /l/ (e.g. 'puzzle' words would be realized like 'pickle' words).

The presumed absence of a feeding interaction and a grandfather effect associated with the 'puzzle > puddle > pickle' problem is an intriguing asymmetry because the two processes of Stopping and Velarization appear to be independent of one another and should be free to vary in their interactions to the full extent possible. The independence of Stopping is supported by its occurrence without Velarization, as demonstrated by those children who replace fricatives with stops, but who also exclude velars from their phonemic inventories (e.g. Maxwell & Weismer 1982). Similarly, Velarization can occur without Stopping, as evidenced by the fact that Velarization persisted in Amahl's grammar for nearly a year after Stopping was suppressed (Macken 1980). The independence of Velarization and Stopping is, thus, supported by the simple occurrence/nonoccurrence of the processes, but the attested range of interactions appears to be limited in the same way that the processes of Labialization and Dentalization were in the current study. The fact that these error patterns do not seem to participate in a feeding interaction or a grandfather effect raises the same questions about whether this asymmetry is an accidental gap or a systematic peculiarity associated with these and other processes. This is an important typological issue because

phonological theory must bring its predictions in line with the systematic occurrence and nonoccurrence of such phenomena.

The 's > θ > f' chain shift and the 'puzzle > puddle > pickle' problem share other substantive properties that further suggest that these observed asymmetries may indeed be systematic. That is, both chain shifts involved a process that changed the [coronal] place feature (Labialization and Velarization, respectively). Both also involved a process that changed a manner feature ([grooved] and [continuant], respectively). The individual processes associated with each chain shift were fully satisfied when one process alone was active in a word. However, when multiple processes were potentially applicable within a word, only one of those processes was permitted to apply, the process that changed the manner feature. For example, in just those cases, there was a preference to preserve [coronal] place. Consequently, both chain shifts resulted in a superficial exception to the place-related process (Labialization and Velarization, respectively).

It is striking that many of the same considerations associated with our proposed modification to OT-CC are at work here also. Recall that we suggested that, when all coronal fricatives are banned by undominated markedness constraints (as they would also have been in Amahl's grammar), ID[continuant] is fixed in its ranking below P_REC(ID[coronal], ID[grooved]). Such a ranking favors the attested Stopping patterns for Amahl and for many of the children in our cross-sectional study. Interestingly, however, the same P_REC constraint from (11) is active here in the case of Amahl and prevents derived stops from feeding Velarization. The difference is that our fixed ranking in the cross-sectional case rendered P_REC inactive by bleeding Labialization; in Amahl's case, P_REC was decisive in eliminating the feeding interaction in favor of the counterfeeding interaction. The OT-CC ranking that we would assume for Amahl's chain shift is given in (15). Many of the constraints are the same as those employed above in (12), except for Velarization. This markedness constraint essentially bans sequences of coronal stops followed by liquids (cf. Dinnsen et al. 2001).

```
(15) Hierarchy for Amahl's chain shift
*θ, *s ≫ ID[grooved] ≫ P_REC(ID[coronal], ID[grooved]) ≫ Velarization ≫
ID[coronal], ID[continuant]
```

In sum, the significance of this account is that a crucial element of it, namely the ranking of ID[continuant] below P_REC(ID[coronal], ID[grooved]), follows from a ranking requirement that was motivated by the need to exclude a feeding interaction involving a different set of processes. We cannot know from these results alone whether these observed asymmetries are peculiar to developing phonologies, specific to processes affecting place and manner features, or if they extend more generally to other processes. More research is called for which systematically investigates the processes associated with other putative chain shifts in both developing and fully developed phonologies to determine whether they exhibit similar asymmetries in their interactions. If other processes were found to exhibit the full range of potential interactions, it might then be possible to identify the properties that distinguish those chain shifts from others that need to be constrained in their interactions.

4. Conclusion

This paper has taken a fresh look at the well known phenomenon of chain shifts, which have posed a long-standing set of theoretical, developmental, and clinical challenges. The findings of our cross-sectional study of the 160 children from the larger archive of 234 young children with phonological delays uncovered some surprising asymmetries in the predicted interactions of the processes associated with the 's > θ > f' chain shift (and the

widely cited 'puzzle > puddle > pickle' problem). More specifically, the predicted feeding interactions and grandfather effects failed to be attested. These results pose new challenges for phonological theories if we are to explain the occurrence of chain shifts in light of the principled nonoccurrence of feeding interactions and grandfather effects associated with these particular processes. From the currently available frameworks, Optimality Theory with Candidate Chains (McCarthy 2007) was identified as a promising starting point for a theoretical revision. The suggestion was to impose a fixed ranking between a particular Precedence constraint and a faithfulness constraint when certain markedness constraints are undominated. However, upon the demotion of one of those markedness constraints, this fixed ranking requirement can be suspended, allowing different permutations of the constraints. It was further suggested that the unattested grandfather effect could be precluded if Comparative Markedness (e.g. McCarthy 2002) were constrained to disallow *θ from being analyzable as $_o$*θ and $_n$*θ. Such an approach would have the effect of precluding certain interactions for some processes while also allowing those interactions for certain other processes. Future research is now warranted that attempts to identify the distinguishing characteristics of those processes that can and cannot interact fully.

APPENDIX

Alternative strategies for avoiding coronal fricatives

(A1) *Coronal Stopping – Child 11* (*age 4;11*)

```
(a) /s/ replaced by coronal stop
bʌt 'bus'      aɪti 'icy'
doʊt 'soap'    əweɪtʊ 'eraser'
(b) /θ/ replaced by coronal stop
dæŋku 'thank you'  tuti 'toothy'
bæt 'bath'     wit 'wreath'
(c) /f/ produced target-appropriately
feɪt 'face'    fæt 'fat'
faɪwʊ 'fire'   eɾʊfɪnt 'elephant'
```

(A2) *Labialization and Stopping – Child 20* (*age 4;7*)

```
(a) /s/ replaced by [t] (Stopping)
dwət 'dress'   maʊt 'mouse'
tɔk 'sock'     tʌn 'sun'
(b) /θ/ replaced by [f] (Labialization)
fʊti 'thirsty'  fʌnʊ 'thunder'
tif 'teeth'    maʊf 'mouth'
(c) /f/ produced target-appropriately
wʊf 'roof'     naɪf 'knife'
goʊfi 'goofy'  faɪjoʊ 'fire'
```

(A3) *Variable substitutes – Child 166* (*age 4;3*)

```
(a) /s/ replaced by [ʔ] or [k]
aɪʔ 'ice'      dʒuʔi 'juicy'
beɪʔbɔ 'baseball'  kɔk 'sock'
```

```
(b) /θ/ deleted or replaced by [ʔ]
maʊw 'mouth'   bæʔi 'bath-i'
riʔ 'wreath'   kʊrʔi 'thirsty'
(c) /f/ produced target-appropriately
faɪv 'five'    jæfɪŋ 'laughing'
faɪʔʊ 'fire'   fɪʔ 'fish'
```

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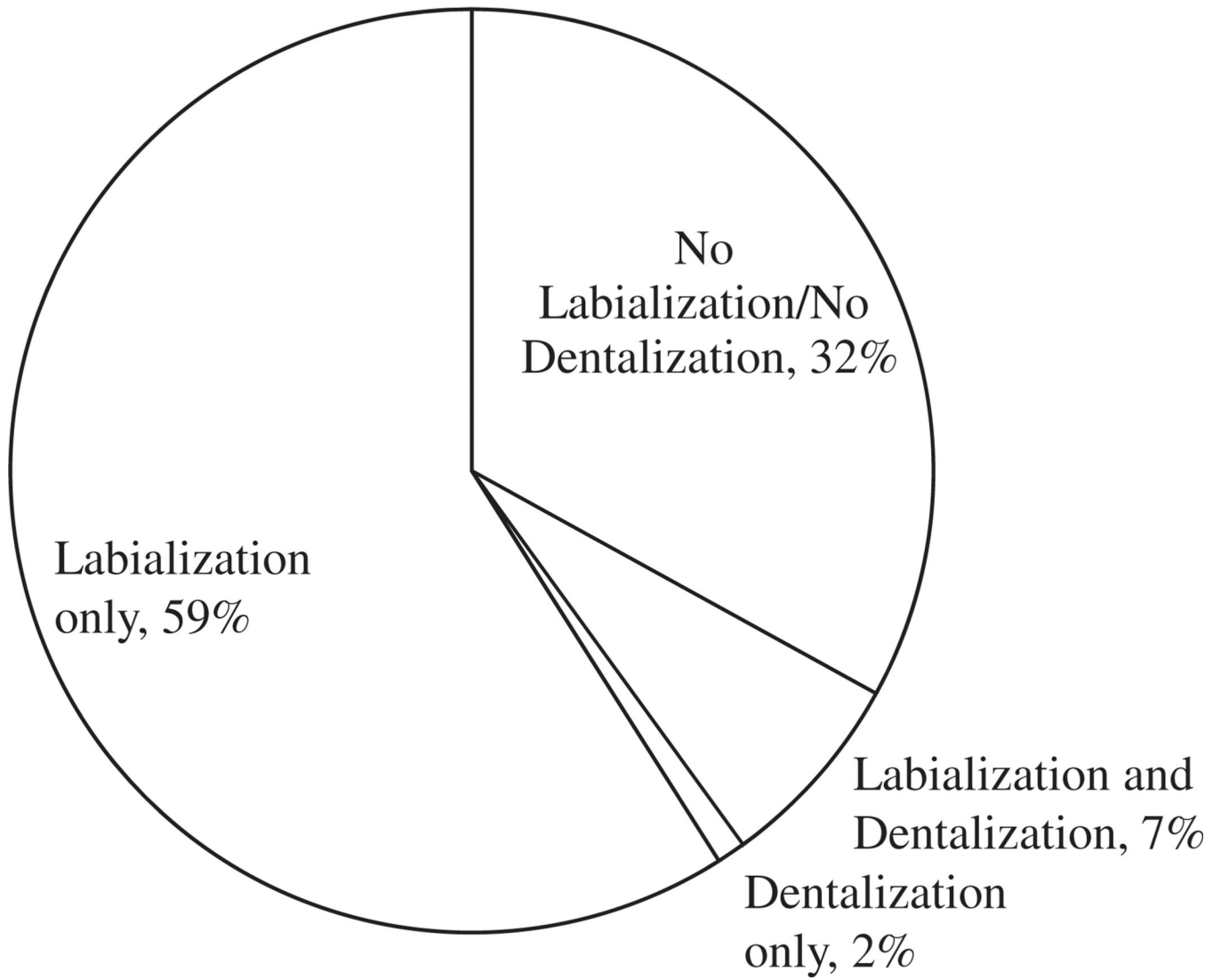
Figure 1.
Proportion of attested typological predictions.