BiPhon-OT for child phonology: Formalizing toddlers' unmarked prosodic structure as an epiphenomenon of interacting phonetic constraints*

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English-speaking toddlers are more likely to omit weak syllables from prosodically unfooted rather than footed positions. This study accounts for these prosodically conditioned omissions using Paul Boersma's BiPhon model in terms of interactions between toddlers' articulatory constraints against short syllables and knowledge of how short unfooted weak syllables are typically realized. This formalizes a proposal by Goffman and Malin and provides an alternative to merely-phonological accounts with phonological Markedness constraints. This work raises the possibility that more child speech production patterns might be modelled as an epiphenomenon of phonetic constraint interactions and illustrates that Paul Boersma's BiPhon model would be perfectly placed for doing so.

1 Introduction

Children who utter their first words or first multi-word utterances, often do not (appear to) produce these completely but rather (appear to) omit syllables that do not fit a basic prosodic template. This can be illustrated by Sesotho[1]-speaking children's tendency to omit the noun class prefix "mo-" before a disyllabic stem

* This work was inspired by over 20 years of being Paul Boersma's student and colleague (Paul and I may differ on when exactly that transition took place, see also Benders & Chládková 2026). In my PhD dissertation, which Paul advised on, I acknowledged him for teaching me that a writer can counteract the absence of prosody by reserving the end of written sentences for what is most important (Benders 2013). Confusingly, that acknowledgement itself was not written in accordance with Paul's rule, thereby hiding that this writing strategy was just one of the many, many things I had the privilege of learning from Paul. May this paper and acknowledgment serve as some correction.

[1] Starting with an example from Sesotho, a Southern-Bantu language of the Niger-Congo language family spoken as the national language of Lesotho and one of the official languages of South-Africa, not only reflects the role that child language research in this language played in the discovery of prosodic constraints on children's omissions of morphological elements, but also Paul Boersma's dedication to inclusive and comprehensive treatment of all languages (and varieties) in linguistic research and teaching.

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(Example 1b) but to realize it before a monosyllabic stem (Example 1a; in these and all following examples, the syllables that are the focus of the examples and this study are underlined, and those that are (likely to be) omitted by children are presented in the adult, but not child realization). Such prosodic conditioning of syllables has possibly been most extensively documented in English[2], a language with strong-weak trochaic feet in which children, mostly those in the toddler age range, are more likely to produce weak syllables that follow a strong syllable, than those that follow another weak syllable or occur word- or phrase initially (Examples 2, 3). As can be seen from Example 3, this phonological conditioning extends to function-word omissions, which are the focus of the present article.

(1) a. Adult: mo-tho
Child: mo-tho
3PFX-stem
'person'

b. Adult: mo-to.go
Child: to.go
3PFX-stem
'soft porridge'

Examples: Tsonope' (2009)

(2) Adult: ba.na.na
Child: na.na

(3) a. Adult: He kicks the piggy
Child: He kicks the piggy

b. Adult: He catches the piggy
Child: He catches piggy

Examples: Gerken (1996)

The phonological conditioning of children's syllable omissions is often understood to result from their constrained prosodic representations. Earlier accounts referred to strong-weak or trochaic rhythmic templates (Allen & Hawkins 1980). Later accounts were formulated with reference to the prosodic hierarchy (Nespor & Vogel 1986; Selkirk 1984) and constraints against syllables falling outside of a disyllabic foot (Demuth & McCullough 2009), or constraints against syllables not being exhaustively[3] governed at each level of the prosodic hierarchy (Gerken 1996).

As can be gauged by the word "constraint", these prosodic accounts of children's preference for "footed" over "unfooted" weak syllables have been

[2] English is a West-Germanic language of the Indo-European language family and spoken as (one of the) official language(s) of 58 sovereign states and 28 non-sovereign entities (Central Intelligence Agence 2026) as counted by Wikimedia Foundation (2026).

[3] An exhaustively governed syllable is governed by a foot, which is in turn governed by a prosodic word, and prosodic phrase—the subsequent levels in the prosodic hierarchy. A not exhaustively governed syllable does, for example, not belong to a foot, but falls directly under a prosodic word.

formalized within Optimality Theory (OT; Prince & Smolensky 1993, 2002). OT can formalize Jakobson's (1941) observation that children's productions are "unmarked" in terms of one or more Markedness constraint(s) outranking one or more Faithfulness constraint(s) (for reviews, see Barlow & Gierut 1999; Boersma & Levelt 2003). The accounts of weak-syllable omissions were no exception and include a high-ranked PARSE-σ constraint, which militates against syllables that are not part of a foot (Demuth 1995; Pater 1997; see Section 2 for a synthesis).

While these phonological formalizations express and thereby capture the prosodic conditioning on English-speaking toddlers' weak syllable omissions, they do not incorporate three aspects of children's *phonetic* abilities and challenges. Firstly, children know the phonetic implementation differences between footed and unfooted articles early on: unfooted syllables are phonetically shorter than footed ones, and this is already observable in 2-year-olds' production of novel content non-words such as [ˈgo.bi] and [go.ˈbi] (Pollock et al. 1993; Schwartz et al. 1996) and in 3-year-olds' production of definite articles in, for example, 'buy the cake' and 'carry the cake' (Cai et al. 2026).[4] Secondly, it appears that producing unfooted weak syllables requires substantial motor specificity: While 4-year-old children (compared to adults) produce longer segments with instable movement modulations, their unfooted weak syllables are surprisingly short and stable (compared to their footed ones[5]), suggesting substantial control is exerted in their articulation (Goffman & Malin 1999). Thirdly, (some) weak syllable omissions must occur at a phonetic level of representation, as (some) children produce phonetic, specifically durational, traces to (some of) the syllables that adult listeners transcribe as omitted, at least in content words (Carter & Gerken 2004). Such covert traces, as also discussed by Levelt (2026), are not compatible with omissions from the surface form, as such phonological omissions must be discrete. A covert trace, instead, shows that a weak syllable is still present in the phonological surface form, and partly omitted at a phonetic level of representation, where omissions can be gradient.

Goffman and Malin (1999) incorporated these phonetic observations into an alternative, but so far unformalized proposal that children's phonologically conditioned weak syllable omissions might emerge from phonetic knowledge and articulatory constraints. The core of their idea is that children are aware of the

[4] The phonetic differentiation between footed and unfooted articles in content words could also reflect phrase-final lengthening, as the words in Pollock et al. (1993) and Schwartz et al. (1996) were elicited in isolation or only with a carrier phrase preceding the target. However, the differentiation observed in articles strongly suggests that children may know about this fine-grained difference in implementation from a very young age.

[5] Children produce footed weak syllables with movement modulations matching those of strong syllables instead, suggesting that the production of unfooted weak syllables is also challenging, but with different demands than unfooted ones (Goffman & Malin 1999).

fine-grained, phonetic implementation distinction between footed and unfooted syllables, and omit unfooted weak syllables until they are able to implement the "adequately specified movement sequence" (Goffman & Malin 1999: 1013). In other words: children omit unfooted weak syllables to avoid realizing them incorrectly. The presence of covert cues or timing slots (Carter & Gerken 2004)[6] is cited in further support of a phonetic mechanism, as this is thought to lead to omissions from the phonetics and thus be more compatible with incomplete omissions than the traditional phonological accounts. I find this idea attractive, as it is parsimonious to consider whether a phonological phenomenon could emerge from children's separately established phonetic knowledge and articulatory constraints, rather than reflect a Markedness constraint such as PARSE-σ, which explicitly states the phonological conditioning. However, this idea still awaits the necessary formalization.

Formalizing Goffman and Malin's (1999) proposal, which is the aim of the present study, requires a model of phonology that also includes phonetic levels of representation. At the end of the 90s, when work on weak-syllable omissions was in full swing (Demuth 1995; Goffman & Malin 1999; Pater 1997) the field was mostly formalizing in merely-phonological[7] OT (Prince & Smolensky 1993, 2002). However, Paul Boersma was already working on the interactions between phonological and phonetic constraints (Boersma 1998), which ultimately resulted in his model of *Bidirectional Phonetics and Phonology* (BiPhon for short; Boersma 2007). BiPhon, whose levels of representations and constraints are visualized in Figure 1, formalizes speaking as well as listening across multiple levels of representation; not only the two phonological and thus discrete representations familiar from traditional OT, but also two phonetic and thus continuous representations, namely the Auditory Form (AudF) and the Articulatory Form (ArtF).[8] The multi-level BiPhon model specifies a constraint family for each single level of representation (much like Markedness constraints for the Surface Form) as well as to evaluate the local connections between adjacent levels of representations (much like Faithfulness constraints for the Surface-Form—Underlying-Form connection). Implemented in OT (among other formalisms), multi-level formalizations in BiPhon can explain a range of

[6] Goffman and Malin (1999) were not clairvoyant, but cited a 1998 precursor to the 2004 article, published as: Carter, A., & Gerken, L. (1998). Evidence for adult prosodic representations in weak syllable omissions of young children. In E. V. Clark (Ed.), *Proceedings of the Annual Child Language Research Forum, Stanford Linguistics Association 29* (pp. 101–110).

[7] This term to describe modelling with the phonological Underlying and Surface Forms and no others is borrowed from Boersma's (2011) *programme for bidirectional phonology and phonetics and their acquisition and evolution.*

[8] In addition to these four, BiPhon includes several higher-level representations, such as the Morphological Form, which are not considered here.

phenomena in terms of interactions between phonetic (and phonological) constraints (see review in: Boersma 2011) and can even explain Markedness-looking effects without reference to a Markedness constraint (Boersma 2005). BiPhon thus provides the machinery required to formalize Goffman and Malin's (1999) idea that toddlers' articulatory challenges producing unfooted syllables (captured by Articulatory constraints) combined with their knowledge about the ideal realizations of footed and unfooted weak syllables (captured by Cue constraints), would result in phonologically conditioned omissions of unfooted (rather than footed) syllables. Moreover, the BiPhon model allows for exploring at which level of representation–phonological or phonetic–these omissions might occur. The present paper will thus investigate if it is possible to provide a BiPhon formalization of Goffman and Malin's (1999) proposal that toddlers' phonologically conditioned weak syllable omissions emerge exclusively from the interaction between phonetic factors, without a role for the phonological PARSE-σ constraint.

Providing a BiPhon account of weak syllable omissions would not only change our understanding of this phenomenon but also illustrate the potential value of this model for understanding child phonology more broadly. Although BiPhon celebrates its 20th birthday next year, in 2027, it has (to the best of my knowledge) not yet been used to explain phonological child production patterns. As toddlers' weak syllable omissions from content words were (among) the first child production patterns to be modelled in merely-phonological OT (Demuth 1995; Pater 1997) and successfully simulated using Boersma's Gradual Learning Algorithm (GLA) (Boersma 1997; Curtin & Zuraw 2002), weak syllable omissions seem a very suitable first child production case for BiPhon OT.

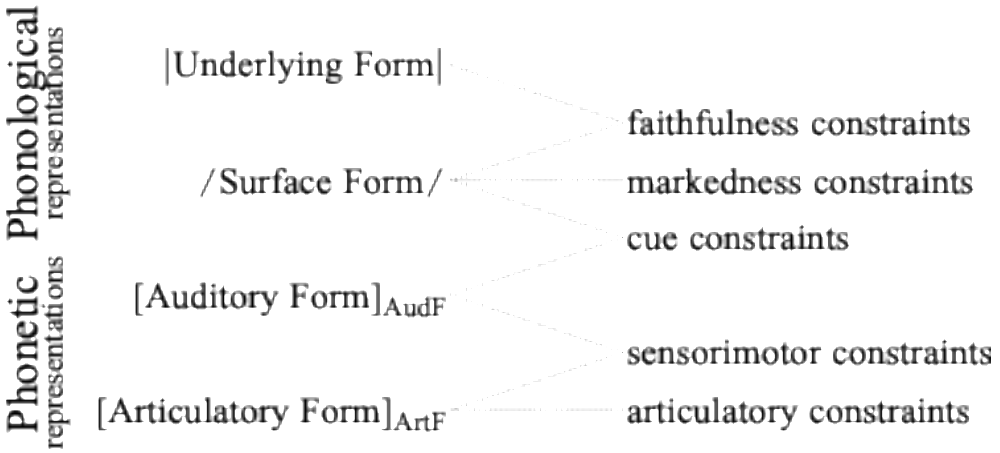


Figure 1: The two phonological and two phonetic levels of representation in the Bidirectional model of Phonetics and Phonology, and the constraints that govern representations at a single level, as well as between levels.

In providing this BiPhon account, I will use examples with function words and model only speaking, assuming parallel evaluation. The decision to focus on function words, specifically articles, rather than weak syllables within content words, was made because phonologically conditioned weak syllable omissions have been observed in function words as well (Demuth & McCullough 2009; Gerken 1996), and because some observations about children's production of sub-phonemic contrasts between footed and unfooted syllables were most convincing in articles (Cai et al. 2026). It is therefore deemed useful to explicitly show that formalizations apply to these types of omissions as well. However, the additional complexity of lexical boundaries will not be considered, making this extension only a first step. The decision to model only speaking parallels previous accounts in merely-phonological OT (Demuth 1995; Pater 1997). The assumption of parallel evaluation follows Boersma (2011), among others, and implies that all phonological and phonetic constraint types will thus interact.

The remainder of this article is organized as follows, with the dual goal of introducing BiPhon to a child-language audience and building towards a BiPhon account of weak syllable omissions: Section 2 presents a synthesized and somewhat BiPhon-ified version of the traditional, merely-phonological accounts with phonological Underlying and Surface Forms (Demuth 1995; Pater 1997). Section 3, then, presents two BiPhon formalizations which incorporate the phonetic Auditory and Articulatory Forms and largely confirm Goffman and Malin's (1999) idea, albeit with some adjustments. Section 4 will summarize the insights gained, provide limitations and directions for future research (to be conducted perhaps together with Paul Boersma), and close off with a conclusion.

2 The traditional, merely-phonological, two-level account

This section provides a merely-phonological two-level analysis of English-speaking toddlers' prosodically conditioned article omissions. It presents a simplified and synthesized version of Demuth (1995) and Pater (1997), translated into BiPhon notations and constraint formulations. This will lay the foundation for the phonological-phonetic BiPhon account in Section 3.

2.1 Analysis ingredients

2.1.1 Levels of representation

The two relevant levels of representation are the phonological Underlying Form |UF| and Surface Form /SF/. The |UF| is assumed to contain target phonemes and lexical stress, following previous OT accounts of children's syllable omissions (Demuth 1995; Pater 1997). At both levels, phonemic content is roughly represented orthographically; the presence of stress is indicated with vowel

capitalization. The relevant properties of the /SF/ are the derived prosodic structure, with syllable boundaries marked with ".", and prosodic feet marked with (). Syllables not contained within () are thus unfooted. If elements from the |UF| are omitted at the /SF/, this is indicated as /000/ for explicitness and *not* to indicate any phonological trace.

2.1.2 Inputs and candidates

|UF| is input and /SF/ is output of merely-phonological speaking. The |UF| inputs are two verb-article sequences: |sEEs the|, where the unstressed article "the" follows the monosyllabic verb "sees", and |cArries the|, where "the" follows the disyllabic, trochaic verb "carries". The /SF/ output candidates for speaking only contrast the presence versus omission of "the": /(sEEs.the)/ versus /(sEEs.000)/, and /(cAr.ries.)the/ versus /(cAr.ries.)000/.

All presented /SF/s preserve the stress from the |UF| and have strong(-weak) (i.e., left-headed, trochaic) feet that incorporate exactly one unstressed syllable to the right of the stressed one into a disyllabic foot whenever possible. The absence of the /SF/s that violate these assumptions (e.g., /(sees.thE)/, /(sEEs.)the/ or /(cAr.ries.the)/, effectively implies some high-ranked constraints, such as TROCHEE and FTBIN. Such implicit constraints are almost necessarily part of any OT account, as no tableau presents the complete candidate set assumed under the Richness of the Base, but this naturally limits the conclusions of the present study.

2.1.3 Constraints

These two-level analyses are conducted with one Faithfulness and one Markedness constraint. The key Faithfulness constraint in Demuth (1995) and Pater (1997) is the traditional MaxI-O constraint, which militates against SFs that miss phonological elements present in the UF. Its BiPhon formulation *|the|/000/ compares the |UF| and /SF/ irrespective of their status as "input" or "output", extending naturally into multi-level analyses, where the SF will be an intermediate level of representation.

(4) *|the|/000/
"Every article in the |UF| has a Correspondent at the /SF/"

The Markedness constraint in the present analyses is PARSE-σ (Prince & Smolensky 1993, 2002), which militates against any syllables that are not parsed as part of a foot:

(5) PARSE-σ
"Each syllable must belong to a foot"

This Markedness constraint is selected from the more extensive constraint sets in Demuth (1995) and Pater (1997), as it most directly governs the phonological conditioning on weak syllable omissions.

2.1.4 Constraint ranking

As is typical for OT modelling of (early) child phonology, the Markedness constraint outranks the Faithfulness constraint.

2.2 Analysis tableaux

These analysis ingredients result in Tableaux 1a,b (or: a formalized merely-phonological toddler) which account for realization of "the" following a monosyllabic verb (Tableau 1a), but omission of that same article following a disyllabic verb (Tableau 1b). For both inputs, the candidate with an omission at /SF/ violates the Faithfulness constraints *|the|/000/. However, because candidate /(cAr.ries.)the/ violates the Markedness constraint PARSE-σ, candidate /(cAr.ries.)000/ is the optimal one for input |cArries the| with a disyllabic verb preceding "the", despite violating the Faithfulness constraint. As neither candidate for input |sEEs the| with a monosyllabic verb violates PARSE-σ, the faithful candidate /(sEEs.the)/ is the optimal one. This merely-phonological toddler's omission of weak syllables in unfooted (but not footed) positions is thus a direct consequence of an interaction between the Markedness PARSE-σ and Faithfulness *|the|/000/ constraints.

Tableaux 1a,b: Traditional OT account, with BiPhon-ified notation, of children's production of |sEEs the|, with no article omission at /SF/, and |cArries the|, with article omission at /SF/.

|sEEs the|	Parse-σ	*|the|/000/
☞ /(sEEs.the)/		
/(sEEs.000)/		*!

|cArries the|	Parse-σ	*|the|/000/
/(cAr.ries.)the/	*!	
☞ /(cAr.ries.)000/		*

3 The new, phonological-phonetic, four-level BiPhon account

Having introduced the traditional, merely-phonological account of children's weak syllable omissions, as well as some BiPhon-ified notations in Section 2, it is now time to address the key question: can the phonological conditioning of

weak articles be accounted for in terms of constraints involving phonetic levels of representation, as proposed by Goffman and Malin (1999), without a role for the PARSE-σ constraint?

3.1 Analysis ingredients

3.1.1 Levels of representations

This analysis is conducted with all four levels of representation from Figure 1. The phonological |UF| and /SF/ will thus be supplemented with two phonetic forms, the Auditory Form [AudF] and the Articulatory Form [ArtF].

The [AudF] will be defined as the auditory strength of the target article syllable, roughly corresponding to its acoustic duration, normalized over variation related to age-related individual differences (Cai et al. 2026), among many others. The remaining, still infinite variation is simplified into a four-way contrast between the $[L]_{AudF}$(ongest) duration typical of stressed syllables, the (inter)$[M]_{AudF}$(ediate) duration more typical of weak footed syllables, the $[B]_{AudF}$(riefest) duration typical of weak unfooted syllables, and the absence of any duration interval associated with a syllable marked with $[0]_{AudF}$ for explicit visibility.

The [ArtF] will be defined as the duration of the articulatory gestures needed to produce the [AudF] four-way contrast: the $[L]_{ArtF}$ gesture to produce $[L]_{AudF}$; the $[M]_{ArtF}$ and $[B]_{ArtF}$ gestures to produce $[M]_{AudF}$ and $[B]_{AudF}$; and the absence of any gesture $[0]_{ArtF}$ to produce no interval $[0]_{AudF}$.

Perfect sensorimotor knowledge, i.e., knowledge of which gestures result in which sounds, is tacitly assumed in Goffman and Malin's (1999) proposal, as children are assumed to know how a lack of control over a certain gesture affects a specific sound. Therefore, sensorimotor connections are not separately modelled and the [AudF] and [ArtF] will be represented as a single phonetic form [AudArtF]. Subscripts clarify when needed whether the representation is $[AudF]_{AudF}$, $[ArtF]_{ArtF}$, or $[AudArtF]_{AudArtF}$.

3.1.2 Inputs and candidates

The input in this multi-level model of speaking is the |UF|. The candidates in these multi-level, parallel evaluations for each |UF| are eight logically possible combinations of the 2 /SF/ (with and without article) and the 4 $[AudArtF]_{AudArtF}$ variations for the article ($[L, M, B, 0]_{AudArtF}$). The listed $[AudArtF]_{AudArtF}$ include the syllables associated with the verbs for completeness, but these are invariant and not part of the evaluation: $[L]_{AudArtF}$ for "sees" and $[LM]_{AudArtF}$ for "carries". The white space between the sounds for the verbs and the article is merely included for legibility and should not be taken to represent a pause in the auditory signal.

3.1.3 Constraints and a-priori ranking within constraint families

In addition to the Faithfulness and Structural constraint from the merely-phonological model, the BiPhon analysis includes Cue and Articulatory constraints. The analysis will not include Sensorimotor constraints, as explained above, or Auditory constraints, as Goffman and Malin's (1999) intuition does not rely on constraints that "perhaps militate against loud or unpleasant noises" (Boersma 2007: 2032).

The first new constraint family, Cue constraints, govern the phonology-phonetics interface and express how phonological categories at the /SF/ should (not) be realized at the [AudF]. They are formulated and notated similarly to the BiPhon-style Faithfulness constraints and militate against ("*") the twelve logically possible combinations of the three prosodic structures for weak syllables at /SF/ (/(w)/=weak footed, /w/=weak unfooted, /000/=absent/omitted) and the four [AudF] strengths ($[L, M, B, 0]_{AudF}$). As these constraints connect qualitatively different types of representations (discrete and continuous), the connections are in principle arbitrary and the constraints militate against both atypical combinations, as in (6), and typical combinations, as in (7):

(6) $*/(w)/[0]_{AudF}$
"A weak footed syllable does not correspond to no duration interval"

(7) $*/w/[B]_{AudF}$
"A weak unfooted syllable does not correspond to the $[B]_{AudF}$(riefest) duration interval"

The ranking of Cue constraints can encode a speaker's knowledge about more or less typical realizations of a /SF/, if the lowest-ranked constraints militate against the most typical connections, and increasing rankings indicate increasing deviations from typicality. As Goffman and Malin (1999) assume that toddlers who omit weak syllables possess such knowledge, this formalization of their proposal ranks cue constraints higher if they militate against more atypical /SF/[AudF] combinations. The degree of atypicality is quantified as the auditory distance between the /SF/'s most typical [AudF] and the [AudF] in the constraint, counting each step along the vector $[L,M,B,0]_{AudF}$ as an auditory distance of 1. For example, the typical realization of /w/ is $[B]_{AudF}$; $[M]_{AudF}$ and $[0]_{AudF}$ are thus each 1 auditory distance removed from this typical realization and $[L]_{AudF}$ is 2 distances removed from it. The relative ranking of the four Cue constraints with /w/ is thus: $*/w/[L]_{AudF}>>*/w/[M,0]_{AudF}>>*/w/[B]_{AudF}$. Generally, cue constraints militating against an auditory distance of 3 (henceforth: Cue_3)>>Cue_2>> Cue_1>>Cue_0.

The second new constraint family, Articulatory constraints, evaluate the [ArtF] as a single level of representation and militate against making (difficult) articulatory gestures. The articulatory constraints in this analysis are *$[B]_{ArtF}$, against producing the challenging briefest gestures, *$[M]_{ArtF}$, against producing the somewhat challenging gestures of intermediate length, and *$[L]_{ArtF}$ against exerting the effort of producing the—in-principle easy—long articulatory gestures. While only *$[B]_{ArtF}$ is explicitly mentioned by Goffman and Malin (1999), the others are included here for completeness and, as we will see later, for playing a role in some constraint interactions.

As briefer articulatory gestures are presumed to be more challenging and longer ones the easiest (see Section 1, including footnote 4, about the footed weak syllables of intermediate duration), these articulatory constraints will be ranked *$[B]_{ArtF}$ >> *$[M]_{ArtF}$ >> *$[L]_{ArtF}$.

3.1.4 A-priori ranking between constraint families

As this analysis is aimed at determining whether phonologically conditioned syllable omissions can emerge from constraints involving phonetic levels of representation, the Markedness constraint PARSE-σ will be ranked lowest in all analyses. To reflect children's knowledge of typical realizations of syllable types, cue constraints Cue_0 (which militate *against* such typical realizations) will be the next-lowest ranked, right above PARSE-σ.

The analyses will investigate the ranking of the Faithfulness constraint *|the|/000/ relative to others and will reveal that this phonological constraint plays a role in the constraint interactions (somewhat contrary to Goffman and Malin's (1999) proposal).

For simplicity, Cue constraints {Cue_3>>Cue_2>>Cue_1} will be treated as a block for simplicity, and its ranking relative to other constraints will be investigated. The Articulatory constraint *$[B]_{ArtF}$, which plays a key role in Goffman and Malin's (1999) proposal can be separated from {*$[M]_{ArtF}$>>*$[L]_{ArtF}$} by other constraints, whereas the latter will be kept together for simplicity.

3.2 Analysis: constraint rankings and example tableaux

The multi-level BiPhon analyses with these analysis ingredients render two different constraint rankings (or: two different formalized phonological-phonetic toddlers) compatible with toddlers' prosodically conditioned weak syllable omissions and Goffman and Malin's (1999) proposal for the underlying, phonetic mechanism. The first formalized phonological-phonetic toddler omits unfooted weak syllables at the phonological /SF/ and the second formalized phonological-phonetic toddler omits them in the phonetics. Both formalized toddlers will be presented as a figure visualizing the required and optional constraint rankings,

alongside tableaux exemplifying one of these possible rankings and the relevant constraint interactions.

Before these two rankings (or toddlers) are presented, this result section will first introduce the constraint ranking and a tableau necessary to account for the realization of the article for input |sEES the|. This does not constitute a full-fledged toddler by itself but a precondition for any complete phonological-phonetic analysis of phonologically conditioned article omissions from the unfooted (and not footed) context.

As will be detailed in this section, modelling article realizations for input |sEES the| requires high-ranked $Cue_{3,2,1}$ and *|the|/000/ constraints. Article omissions for input |cArries the| require an additionally high-ranked $*[B]_{Art}$ constraint, with the difference between the toddlers with phonological and phonetic omissions lying in the ranking of $*[B]_{Art}$ relative to $Cue_{3,2,1}$ and *|the|/000/.

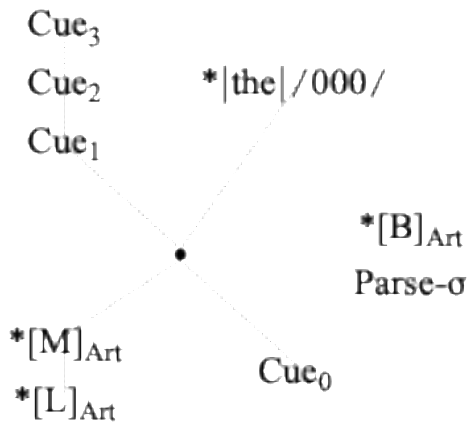


Figure 2: The required strict constraint rankings for production of |sEEs the| with article realization at both phonological and phonetic levels of representation.

3.2.1 Precondition: Production of input |sEEs the| with article realization

Figure 2 visualizes the required and optional constraint rankings to model the phonological and phonetic realization of an article for input |sEES the|. In this and subsequent figures, constraints that are connected via dotted lines are strictly ranked (the constraints printed higher in the figure outrank those printed lower) and the black dots are nodes to indicate optional ranking of the constraint clusters connected above (or below) them. To summarize Figure 2, $Cue_{3,2,1}$ and *|the|/000/ must outrank $*[M]_{Art}$ and $*[L]_{Art}$ and Cue_0. $*[B]_{Art}$ and PARSE-σ are not connected to other constraints, as their ranking has no implications for the complete realization of the article in |sEEs the|.

Tableau 2 displays an evaluation with one of the possible constraint rankings. The unranked constraints $*[B]_{ArtF}$ and Parse-σ are included and ranked

as low as possible given the a-priori ranking within constraint families (see Subsection 3.1.3).

Tableau 2: One possible constraint grammar and evaluation for production of |sEEs the| with article realization at both phonological and phonetic levels of representation; this is a preliminary step to modelling the phonological-phonetic toddler.

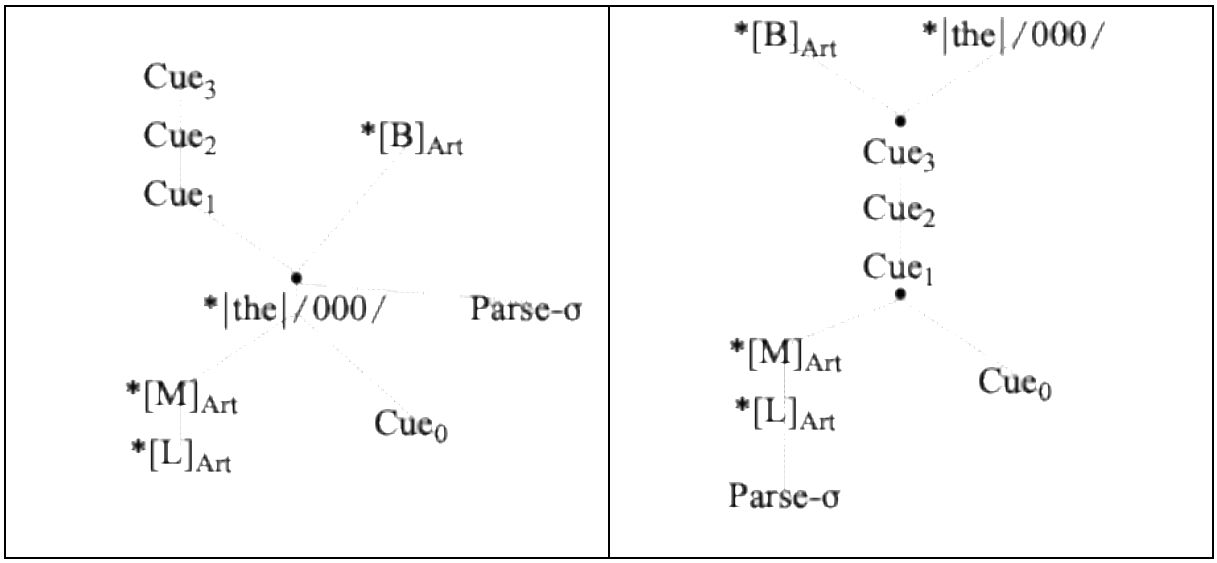
|sEEs the|	Cue$_3$ */0/ [L]$_{AudF}$	Cue$_2$ */(w)/ [0]$_{AudF}$	Cue$_2$ */0/ [M]$_{AudF}$	Cue$_2$ */w/ [L]$_{AudF}$	Cue$_1$ */(w)/ [B]$_{AudF}$	Cue$_1$ */(w)/ [L]$_{AudF}$	Cue$_1$ */0/ [B]$_{AudF}$	Cue$_1$ */w/ [0]$_{AudF}$	Cue$_1$ */w/ [M]$_{AudF}$	*|the|/000/	*[B]$_{ArtF}$	*[M]$_{ArtF}$	*[L]$_{ArtF}$	Cue$_0$ */(w)/ [M]$_{AudF}$	Cue$_0$ */0/ [0]$_{AudF}$	Cue$_0$ */w/ [B]$_{AudF}$	Parse-σ
/(sEEs.the)/ [LM L]						*							*				
☞ /(sEEs.the)/ [LM M]												*		*			
/(sEEs.the)/ [LM B]					*						*						
/(sEEs.the)/ [LM 0]		*															
/(sEEs.000)/ [LM L]	*!										*			*			
/(sEEs.000)/ [LM M]			*								*		*				
/(sEEs.000)/ [LM B]							*				*	*					
/(sEEs.000)/ [LM 0]											*!					*	

This preliminary toddler's high-ranked knowledge of what would constitute atypical realizations of syllable types, captured by Cue$_{3,2,1}$, ensures that she prefers candidates with a typical [AudArtF] realization of the /SF/, either /(sEEs.the)/[M]$_{AudF}$ or /(sEEs.000)/[0]$_{AudF}$. The child's also high-ranked knowledge that the |UF| should ideally be kept intact, captured by *|the|/000/, ensures that she prefers candidates with (rather than without) an article at /SF/, namely /(sEEs.the)/. Both these types of knowledge are more important than the toddler's desire to avoid articulatory effort, captured by *[B,M,L]$_{ArtF}$. In addition, *|the|/000/ outranking Cue$_0$, ensures that the toddler avoids omissions rather than typical realizations of the syllable types.[9] The preliminary formalized toddler's optimal candidate is thus one with an article at /SF/ and a typical realization of that syllable type at [AudArtF]: /(sEEs.the)/[M]$_{AudF}$.

Readers might wonder to what extent this constraint ranking is more likely than some other rankings. However, the objective in this subsection was more

[9] Readers who feel that this sentence is counter-intuitive, would have a point. The Cue$_0$ constraints are atypical compared to other OT constraints, as they militate *against* connections that the speaker should know to be typical. The Cue$_0$ constraints are thus similar to Faithfulness constraints such as *|the|/the/ or *|000|/000/, which are not typically included in OT analyses. These Cue$_0$ constraints are included here to illustrate the arbitrariness of connections between discrete and continuous representations at the phonology-phonetics interface.

modest, namely to merely find the constraint ranking needed to account for realization of articles following a monosyllabic verb. As a complete account of phonologically conditioned article omissions must also include these realizations, this constraint ranking serves as a baseline when finding a ranking to account for omissions following a disyllabic verb.



Figures 3a,b: a/left: the required constraint rankings for production of the article in |cArries the| as /0/[0], i.e., with article omission at both the phonological /SF/ and phonetic [AudArtF] level of representation; this is the first formalized phonological-phonetic toddler. b/right: The required constraint rankings for production of the article in |cArries the| as /the/[0], i.e., with article realization at the phonological /SF/, but omission at the phonetic [AudArtF] level of representation; this is the second formalized phonological-phonetic toddler.

3.2.2 Production of |cArries the| with article omissions

The second investigatory step was to find the constraint ranking(s) that result(s) in omissions of articles following a disyllabic verb, while preserving the realization of articles following a monosyllabic verb and keeping PARSE-σ low-ranked and never critical to the evaluation.

Figure 3a visualizes the rankings of a formalized phonological-phonetic toddler with phonological (as well as phonetic) omissions; Figure 3b shows the rankings of a formalized phonological-phonetic toddler with phonetic-only omissions. In both rankings, $*[B]_{ArtF}$ is among the highest-ranked constraints. The key difference is that $Cue_{3,2,1}$>>*|the|/000/ results in phonological omissions at /SF/ (as well as phonetic omissions), while *|the|/000/>>$Cue_{3,2,1}$ results in realization of the article at /SF/ and phonetic-only omissions at [AudArtF]. In brief: phonological-phonetic toddlers who prioritize phonetic implementation produce phonological omissions, while phonological-phonetic toddlers who prioritize phonological implementation produce phonetic omissions.

Tableaux 3a,b: One of the possible constraint grammars for the first formalized phonological-phonetic toddler, resulting in phonologically conditioned article omission only following a disyllabic verb at the phonological and phonetic levels of representation, showing evaluations for production of |sEEs the| (a/top) and |cArries the| (b/bottom).

|sEEs the|	*[B]$_{ArtF}$	Cue$_3$ */0/[L]$_{AudF}$	Cue$_2$ */(w)/[0]$_{AudF}$	Cue$_2$ */0/[M]$_{AudF}$	Cue$_2$ */w/[L]$_{AudF}$	Cue$_1$ */(w)/[B]$_{AudF}$	Cue$_1$ */(w)/[L]$_{AudF}$	Cue$_1$ */0/[B]$_{AudF}$	Cue$_1$ */w/[0]$_{AudF}$	Cue$_1$ */w/[M]$_{AudF}$	*|the|/000/	*[M]$_{ArtF}$	*[L]$_{ArtF}$	Cue$_0$ */(w)/[M]$_{AudF}$	Cue$_0$ */0/[0]$_{AudF}$	Cue$_0$ */w/[B]$_{AudF}$	Parse-σ
/(sEEs.the)/ [LM L]							*						*				
☞ /(sEEs.the)/ [LM M]												*		*			
/(sEEs.the)/ [LM B]	*!					*											
/(sEEs.the)/ [LM 0]			*														
/(sEEs.000)/ [LM L]		*!									*		*				
/(sEEs.000)/ [LM M]				*							*	*					
/(sEEs.000)/ [LM B]	*!							*			*						
/(sEEs.000)/ [LM 0]											*!				*		

|cArries the|	*[B]$_{ArtF}$	Cue$_3$ */0/[L]$_{AudF}$	Cue$_2$ */(w)/[0]$_{AudF}$	Cue$_2$ */0/[M]$_{AudF}$	Cue$_2$ */w/[L]$_{AudF}$	Cue$_1$ */(w)/[B]$_{AudF}$	Cue$_1$ */(w)/[L]$_{AudF}$	Cue$_1$ */0/[B]$_{AudF}$	Cue$_1$ */w/[0]$_{AudF}$	Cue$_1$ */w/[M]$_{AudF}$	*|the|/000/	*[M]$_{ArtF}$	*[L]$_{ArtF}$	Cue$_0$ */(w)/[M]$_{AudF}$	Cue$_0$ */0/[0]$_{AudF}$	Cue$_0$ */w/[B]$_{AudF}$	Parse-σ
/(cAr.ries.)the/ [LM L]					*								*				*
/(cAr.ries.)the/ [LM M]										*		*					*
/(cAr.ries.)the/ [LM B]	*!															*	*
/(cAr.ries.)the/ [LM 0]									*								*
/(cAr.ries.)000/ [LM L]		*!									*		*				
/(cAr.ries.)000/ [LM M]				*							*	*					
/(cAr.ries.)000/ [LM B]	*!							*			*						
☞ /(cAr.ries.)000/ [LM 0]											*						

Tableaux 3a,b present evaluations with one of the rankings of the first formalized phonological-phonetic toddler (Figure 3a), showing that the omissions are indeed phonologically conditioned (i.e., occur for input |cArries the| but not for |sEEs the|); reflect an interaction of Articulatory, Cue, and Faithfulness constraints, with no role for the Markedness constraint Parse-σ; and occur in the phonological /SF/.

For both the inputs |sEEs the| and |cArries the|, the high-ranked *[B]$_{ArtF}$, eliminates the candidates with a very brief article realization. The effect of the also high-ranked Cue$_{3,2,1}$ diverges between the two inputs, because these inputs are associated with, respectively, footed versus unfooted articles at /SF/. This, in turn, results in different roles for *|the|/000/ in the evaluation of these inputs.
For input |sEEs the|, the Cue constraints eliminate all /SF/[AudF] combinations apart from either /(sEEs.the)/[LM M]$_{AudF}$ or /(sEEs.000)/[LM 0]$_{AudF}$ as containing atypical realizations. As neither of the [ArtF] associated with these forms violated *[B]$_{ArtF}$, *|the|/000/ plays a role in the selection, and the optimal candidate is the one preserving "the" at /SF/: /(sEEs.the/[LM M]$_{AudArtF}$.

In contrast, for input |cArries the|, Cue$_{3,2,1}$ eliminate all /SF/[AudF] combinations apart from /(cAr.ries.)the/[LM B]$_{AudF}$ or /(cAr.ries.)000/[LM 0]$_{AudF}$ as atypical.However, as [LM B]$_{AudF}$ violated the high-ranked *[B]$_{Art}$, evaluation against just Cue and Articulatory constraints is sufficient to determine that the optimal candidate is the one with no syllable at either /SF/ or [AudF]: /(cAr.ries.)000/[LM 0]$_{ArtAudF}$, irrespective of this form's violation of *|the|/000/.

To summarize, this first formalized phonological-phonetic toddler shows that it is possible to account for toddlers' phonologically conditioned syllable omissions as an emergent consequence of their articulatory difficulties with very brief syllables in interaction with their knowledge that unfooted syllables should typically be very brief—exactly as proposed by Goffman and Malin (1999). However, this formalization also reveals that when these two phonetic considerations are more important than preservation of phonological elements, the omission will occur in the phonology, not the phonetics—in contrast to the suggestion by Goffman and Malin (1999).

Let's now turn to Tableaux 4a,b, which present an evaluation with one of the possible constraint rankings of the second formalized phonological-phonetic toddler (Figure 3b), showing that these omissions are also phonologically conditioned, i.e., occur only following a disyllabic verb; reflect a different interaction of Articulatory, Cue, and Faithfulness constraints than observed for the first formalized toddler but again without a role for PARSE-σ; and that article omissions occur only at the [AudArtF], not the /SF/.

As for the first phonological-phonetic toddler, the high-ranked *[B]$_{ArtF}$ eliminates any candidates with a very brief realization of the article for both the inputs |sEEs the| and |cArries the|. In contrast to the grammar of the first phonological-phonetic toddler with phonological omissions, the similarly high-ranked *|the|/000/ results in the elimination of candidates with syllable omissions at /SF/ for inputs |sEEs the| as well as |cArries the|. The violation patterns of the intermediately ranked Cue$_{3,2,1}$ differ between the two inputs, because of the different /SF/ structures, and result in elimination of the candidates with atypical realizations of the respective /SF/.

Tableaux 4a,b: One of the possible constraint grammars of the second formalized phonological-phonetic toddler, resulting in phonologically conditioned article omission only following a disyllabic verb at only the phonetic level of representation, showing evaluations for production of |cArries the| (a, top) and |sEEs the| (b, bottom).

|sEEs the|	*[B]$_{ArtF}$	*|the|/000/	Cue_3 */0/[L]$_{AudF}$	Cue_2 */(w)/[0]$_{AudF}$	Cue_2 */0/[M]$_{AudF}$	Cue_2 */w/[L]$_{AudF}$	Cue_1 */(w)/[B]$_{AudF}$	Cue_1 */(w)/[L]$_{AudF}$	Cue_1 */0/[B]$_{AudF}$	Cue_1 */w/[0]$_{AudF}$	Cue_1 */w/[M]$_{AudF}$	*[M]$_{ArtF}$	*[L]$_{ArtF}$	Cue_0 */(w)/[M]$_{AudF}$	Cue_0 */0/[0]$_{AudF}$	Cue_0 */w/[B]$_{AudF}$	Parse-σ
/(sEEs.the)/ [LM L]								*					*				
☞ /(sEEs.the)/ [LM M]												*		*			
/(sEEs.the)/ [LM B]	*!						*										
/(sEEs.the)/ [LM 0]				*													
/(sEEs.000)/ [LM L]		*!	*										*				
/(sEEs.000)/ [LM M]		*!			*							*					
/(sEEs.000)/ [LM B]	*!	*							*								
/(sEEs.000)/ [LM 0]		*!													*		

|cArries the|	*[B]$_{ArtF}$	*|the|/000/	Cue_3 */0/[L]$_{AudF}$	Cue_2 */(w)/[0]$_{AudF}$	Cue_2 */0/[M]$_{AudF}$	Cue_2 */w/[L]$_{AudF}$	Cue_1 */(w)/[B]$_{AudF}$	Cue_1 */(w)/[L]$_{AudF}$	Cue_1 */0/[B]$_{AudF}$	Cue_1 */w/[0]$_{AudF}$	Cue_1 */w/[M]$_{AudF}$	*[M]$_{ArtF}$	*[L]$_{ArtF}$	Cue_0 */(w)/[M]$_{AudF}$	Cue_0 */0/[0]$_{AudF}$	Cue_0 */w/[B]$_{AudF}$	Parse-σ
/(cAr.ries.)the/ [LM L]						*							*				*
/(cAr.ries.)the/ [LM M]											*	*!					*
/(cAr.ries.)the/ [LM B]	*!															*	*
☞ /(cAr.ries.)the/ [LM 0]										*							*
/(cAr.ries.)000/ [LM L]		*!	*										*				
/(cAr.ries.)000/ [LM M]		*!			*							*					
/(cAr.ries.)000/ [LM B]	*!	*							*								
/(cAr.ries.)000/ [LM 0]		*!															

For input |sEES the| with /SF/ /(sEEs.the)/, $Cue_{3,2,1}$ eliminate all but [LM M]$_{AudF}$ as atypical realizations of the footed article. This leaves /(sEEs.the)/[LM M]$_{AudArtF}$ as the optimal candidate, despite its violation of some low-ranked constraints, including *[M]$_{ArtF}$.

In contrast, for input |cArries the| with /SF/ /(cAr.ries.)the/, $Cue_{3,2,1}$ eliminate all but $[LM\ B]_{AudF}$ as atypical realizations of the unfooted article. The only remaining candidates are those with the somewhat-too-strong or somewhat-too-weak article realizations, $[LM\ M]_{AudArtF}$ or $[LM\ 0]_{AudArtF}$. Out of these, only $[LM\ M]_{AudArtF}$ violates the low-ranked *[M]Art. The optimal candidate is therefore the one with an article at /SF/ but no realization thereof in the phonetics: /(cAr.ries.)the/$[LM\ 0]_{AudArtF}$, despite its violation of a low-ranked Cue_0.

To summarize, this second formalized phonological-phonetic toddler shows a different way in which toddlers' phonologically conditioned weak-syllable omissions could emerge from their articulatory constraints and phonetic knowledge. In contrast to the first phonological-phonetic toddler, this second one has such omissions only in the phonetics but not in the phonology, in line with Goffman and Malin's (1999) proposal. However, this specific constraint interaction relies on two further factors beyond those mentioned in that proposal. Firstly, the phonological-phonetic toddler with phonetics-only omissions highly prioritizes preserving elements from the phonological Underlying Form when they plan their utterance phonologically in the Surface Form. Secondly, these omissions are not just the result of the toddler's knowledge of the fine-grained, phonetic distinction between footed and unfooted syllables combined with an inability to implement the "adequately specified movement sequence"–Goffman and Malin's (1999) original proposal–but also reflect that she avoids exerting articulatory effort on the production of an Auditory Form that is not the ideal realization of the intended Surface Form. Phonetic-level omissions thus occur as the result of more Articulatory constraints with a stronger role for phonology than Goffman and Malin (1999) had proposed.

4 Discussion

In this article, I set out to provide a BiPhon-OT (Boersma 2007) formalization of Goffman and Malin's (1999)'s idea that English-speaking toddlers' omissions of unfooted weak syllables emerge from phonetic knowledge and constraints. This has resulted in two formalized phonological-phonetic toddlers who both display phonologically conditioned weak-syllable omissions as the result of an interaction between high-ranked constraints involving phonetic levels of representations: Articulatory and Cue constraints. The constraint rankings leave no critical role for the phonological Markedness constraint PARSE-σ, which was critical to the omissions by the merely-phonological toddler, from traditional two-level OT accounts of this pattern (Demuth 1995; Pater 1997).

The two formalized phonological-phonetic toddlers, and a comparison between them, highlight that a single phonetic factor (e.g., articulatory challenges) cannot be straightforwardly connected to a single, phonetic adaptation in toddlers'

speech production (e.g., phonetics-only omissions). Rather, both phonological-phonetic toddlers omit unfooted syllables as the result of at least two interacting phonetic factors: they know that a very brief syllable would be the most typical phonetic realization of an unfooted article (Cue constraints) but do not have the motor control to articulate it (Articulatory constraint). The interaction is even more complex for the second phonological-phonetic toddler, involving further constraints on minimizing any articulatory effort (other Articulatory constraints) as well as constraints on keeping phonological structure intact (Faithfulness constraints). Moreover, in contrast to Goffman and Malin's (1999) suggestion that omissions due to phonetic knowledge and constraints would occur only at the phonetic levels of representation, this was only true for the second phonological-phonetic toddler and due to their higher priority on phonological consistency than on the typicality of phonetic realizations (the Faithfulness constraint outranks the Cue constraints). The first phonological-phonetic toddler, in contrast, omits weak syllables in the phonological Surface Form because their priorities are reversed: phonetic typicality over phonological consistency (Cue constraints outrank the Faithfulness constraint). This shows that high-ranking constraints involving phonetic levels of representation may in fact result in a phonological omission. These two formalizations, implemented in BiPhon across four levels of phonological and phonetic representations, thus highlight that the nature and impact of any phonetic difficulty must be understood in light of all other relevant phonetic and phonological factors.

What are the implications of this insight for (OT) accounts of child phonology more generally, and the role that BiPhon could play in those? Traditional OT explains child production patterns in terms of high-ranking Markedness constraints (Barlow & Gierut 1999; Boersma & Levelt 2003). However, the present analyses suggest that the high-ranked PARSE-σ constraint from merely-phonological accounts has no explanatory power once interacting phonetic factors and phonological faithfulness are considered. While this conclusion cannot be automatically extended to other Markedness constraints (such as the implicitly assumed TROCHEE or FTBIN constraints, see Section 2.1.2) or beyond weak-syllable omissions, it warrants further investigation whether other (presumed) phonological constraints or phonological-looking child production patterns can be reduced to interacting phonetic factors. Such an endeavour would result in more parsimonious explanations of children's speech production patterns and a more fine-grained understanding of the biases and knowledge shaping them. It is my hope that the present study shows the value of Paul Boersma's BiPhon model for such an undertaking.

The work presented here could be extended by accounting for more empirical observations about children's weak syllable omissions and realizations. Firstly, the present formalizations simplifyingly assume that children produce

footed weak syllables correctly, contrary to the evidence that these might be articulated more like strong syllables (Goffman & Malin 1999). Secondly and relatedly, this study only formalized those toddlers who produce footed weak syllables and omit the unfooted ones. However, at least one child in the published literature (and thus presumably other children in the population) rather produced all their function words as prosodic words, thus changing the prosodic structure to no longer contain weak syllables and the gestures to no longer needing to be brief and thus constrained (Demuth & McCullough 2009). Thirdly, this study could not model the possibility that (some) toddlers (may) produce covert traces to their omitted weak syllables (Carter & Gerken 2004), due to the very coarsely formulated Cue and Articulatory constraints. These three limitations should be addressed in future work formalizing a wider range of production patterns as well as the phonetic details of the (transcribed) omissions and realizations.

The analyses from this study could be strengthened by further experiments to empirically test some of the underlying assumptions. Most critically, the present work assumes that toddlers know the typical phonetic realizations of unfooted and footed weak syllables already during the omission stage. The evidence thereof in fact comes from children's differentiation during early productions (Cai et al. 2026; Pollock et al. 1993; Schwartz et al. 1996), which necessarily follows the (optional) omission stage modelled here. A further and more stringent test of the assumption would thus be to assess whether infants or still-omitting toddlers are sensitive to the match between the prosodic position of a weak syllable and its auditory strength. Such research has the potential to reveal young children's sensitivity to the prosodic hierarchy, thereby also extending existing evidence on infants' and young toddlers' sensitivity to word-level rhythm, phrase-level melody and pauses structures (reviewed in several chapters in the volume edited by Prieto and Esteve-Gibert 2018) as well as their sensitivity to coarticulatory dependence of "the" on the subsequent linguistic material (Mahr et al. 2015).

Further limitations of the present study relate to the static and coarse-grained nature of the BiPhon formalizations, which could be relatively easily addressed by further building on Paul Boersma's work. Firstly, the omission patterns are deterministic for the formalized toddlers but probabilistic in real toddlers, who also omit some weak syllables from footed contexts, but typically more (although not necessarily all) from unfooted contexts. Such probabilistic patterns can be straightforwardly accounted for by adopting stochastic constraint positions along a continuous scale (Boersma 1998). Secondly, only a subset of all possible constraint rankings was considered, as several constraint (sub-)families were kept together as a block, and the two presented rankings for the phonological-phonetic toddlers were hand-picked to display the desired production behaviour. This raises questions about other constraint rankings that

might display the same production patterns, whether all these constraint rankings are equally likely to arise during learning, and whether they are part of the same or different developmental paths. Such issues would need to be investigated with learning simulations, for example using the Gradual Learning Algorithm (Boersma 1997). Finally, the constraints referring to phonetic levels of representation were formulated to be very coarse-grained, discretizing both auditory forms and articulatory forms into only four categories, effectively bypassing the entire idea of continuous representations. Moreover, the analyses did not consider the multitude of auditory properties and articulatory gestures with which syllable types are realized. Incorporating more fine-grained constraints along multiple dimensions would make the formalizations more realistic and provide a step towards modelling covert cues (Carter & Gerken 2004). The resulting large number of candidates could be dealt with using candidate graphs (Boersma & Van Leussen 2017), although a better treatment of the continuity and multidimensionality of phonetic representations might be afforded by the neural-network models already developed for BiPhon (Boersma et al. 2020). These would all present natural next steps for improving the presented formalizations of toddlers' weak-syllable omissions, as well as for highlighting the many ways in which Paul Boersma's work can help improve our understanding of child phonology more generally.

4.1 General conclusion

To conclude, this paper used Paul Boersma's BiPhon model to formalize through an interaction of Articulatory, Cue, and other constraints Goffman and Malin's proposal that children avoid producing unfooted weak syllables altogether because they know these syllables should be reduced, but also know they cannot produce the necessary constrained articulations. The results provide an alternative to the widely accepted, merely-phonological OT accounts of these weak-syllable omissions, show that a phonologically conditioned production pattern can emerge from mainly phonetic factors, but also show that phonetic mechanisms may not have merely phonetic consequences. More broadly speaking, this study highlights the potential value of Boersma's BiPhon model for formalizing the contribution of interacting phonetic and phonological constraints to children's speech production patterns.

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