An analysis of velar fronting in child phonology based on a longitudinal corpus study*

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Cho, Hyesun. 2014. An analysis of velar fronting in child phonology based on a longitudinal corpus study. *Studies in Phonetics, Phonology and Morphology* 20.2. 207-228. Velar fronting is a well-known phenomenon in child phonology where velars in prosodically strong position are produced as coronals, due to child's articulatory limitations. Velar fronting is one of the unnatural phonological processes that are observed only in child, not in any known adult system. Velar fronting in one child is closely investigated through a longitudinal study using the CHILDES corpus. It turns out that the acquisition of velar production is achieved during a period of four months, yielding an S-shaped developmental curve. The result of the longitudinal study supports a view that in phonological acquisition, constraint demotion does not take place immediately but gradually as the Gradual Learning Algorithm (GLA) predicts. Assuming that velar fronting arises from the gap between perception and production in child, an Optimality-Theoretic analysis is provided, based on the framework in Pater (2004). Finally, a learning simulation is conducted using the GLA with the proposed constraint schema, fed by the real-life corpus data. The results show how ranking values of relevant constraints change over time in a child. **(Dankook University)**

Keywords: Velar fronting, child phonology, acquisition, production, perception, Gradual Learning Algorithm, CHILDES

1. Introduction

Velar fronting (VF) is the phenomenon where velar stops in prosodically strong positions are produced as coronals in children's speech, whereas those in prosodically weak positions are pronounced as velars (Ingram 1974, Chiat 1983, Bills and Golston 2002, Pater 2004, Inkelas and Rose 2003, 2008, among others). Prosodically strong positions are stressed syllables and/or word-initial syllables (Bills and Golston 2002, Keating et al. 2003). Inkelas and Rose (2008) illustrate velar fronting in prosodically strong positions as in (1) (Inkelas and Rose 2008: 710), which are the data from a child E, a monolingual learner of English. The examples in (1) show that target velar stops [k,g] are produced as coronal stops [t,d] in these positions.

(1) VF in onsets of prosodically strong positions

a. Word-initial primary-stressed syllable onset

[t^hʌp]	'cup'	(1;09.23)
[do:]	'go'	(1;10.01)

b. Word-medial primary-stressed syllable onset

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[əˈdɪn] 'again' (1;10.25)
[taˈdɛrə] 'together' (2;01.21)
c. Word-medial secondary-stressed syllable onset
[ˈhewˌtɔptɛə] 'helicopter' (2;00.19)
[ˈhɛksəˌdɔn] 'hexagon' (2;02.22)
d. Word-initial unstressed syllable onset
[tʌnˈdʌktə] 'conductor' (2;01.21)

It is not the case that the child is not able to produce velar stops entirely. Target velars are realized as velars in prosodically weak positions, as shown in (2) (Inkelas and Rose 2008: 711).

(2) Velar productions outside of prosodically strong position onsets
a. Onsets of unstressed syllables
[ˈmɑŋki] 'monkey' (1;08.10)
[ˈbeɟgu] 'bagel' (1;09.23)
b. Word-medial codas
[ˈæktʃwi] 'actually' (1;11.22)
[ˈɑktəgɑn] 'octagon' (2;01.05)
c. Word-final codas
[bɪg] 'big' (1;00.13)
[bʊkʰ] 'book' (1;07.22)

It is well-known that velar fronting arises from child's articulatory limitations in producing velar stops in prosodically strong positions (Pater 2004, Inkelas and Rose 2008: 722ff.). Children have a small oral cavity, compared with a relatively large tongue which almost entirely fill the small oral cavity (Crelin 1987: 94ff., Fletcher 1989). When a child produces a velar stop in a prosodically strong position, the place of articulation of the velar is fronted due to the enhanced movement of the tongue in such positions. For adults, the palate is long enough that the enhanced velar articulation can remain in the velar place of articulation. However, for children, the resulting sound is coronal – the fronted tongue ends up contacting the area of coronals because of the shorter palate.

1.1 A longitudinal study of velar fronting

In this paper I analyzed longitudinal data of velar fronting by a child acquiring American English as his first language during the ages 2;5.18-3;9.02, using a spoken corpus, CHILDES (Child Language Data Exchange System, MacWhinney 2000). Previous longitudinal studies of velar fronting include Smith (1973), Compton and Streeter (1977), Bills and Golston (2002), and Inkelas and Rose (2008), among many others. Children differ in the age when velar fronting stops. Bills and Golston (2002) examined velar fronting of a girl, Sine, during the ages 2;9 – 3;6. In their study, data collection was still in progress at the time the paper was written, so one cannot know when velar fronting ceased. On the other hand, the child 'E' in Inkelas and Rose (2008) displays velar fronting at the ages 1;00.27 - 2;02.28 (the total period of data collection is 0;06.09~3;09.29), i.e., velar fronting ceased at the age 2;02.28. Sine still displayed velar fronting at the age 3;6, whereas the child E stopped velar fronting at 2;02.28. Both were normally developing children. A phonologically delayed child, Stephen, showed velar fronting at age 5;9 (Chiat 1983: 289).

The present study differs from the previous ones for the following respects. First, one of the goals of the present longitudinal study is to see how gradual or abrupt the learning curve is, which may have implications on the study of the grammar learning. It has been known that phonological learning typically follows an S-shaped curve (e.g., onset cluster production (Becker and Tessier 2011)), though some processes are U-shaped (e.g., consonant harmony (Becker and Tessier 2011), irregular morphology (Marcus et al. 1992)). I will show the learning trajectory of velar fronting based on a longitudinal exploration of the corpus. The learning trajectory provides empirical evidence for the question of whether constraints demoted immediately (*Constraint Demotion Algorithm* (CDA), Tesar and Smolensky 1998) or the learning takes place gradually (*Gradual Learning Algorithm* (GLA), Boersma and Hayes 2001). The GLA offers a theoretical framework where variable frequencies in a synchronous corpus can be accounted for, and so it has been more often used to explain phonological variation. The present paper combines a GLA analysis with longitudinal, rather than synchronous, data. It is a contribution of this paper to show how GLA grammar learning occurs over the course of time based on real-life data.

Second, the majority of the longitudinal studies on velar fronting used transcribed data, rather than multimedia data such as audio files. For example, Inkelas and Rose (2008) used the data which were collected in a diary setting by the parents who were both trained phonologists. These data were transcribed phonetically, and so did the majority of the longitudinal studies (2008: 709). The current study differs from these in that a spoken corpus, CHILDES, is used.

1.2 Theoretical framework

Velar fronting is unique in children and never found in adults' speech or any known languages and dialects. Some phonological processes are found only in child. Buckley (2003) illustrates several child-unique unnatural phonological processes, e.g., more contrasts in codas than in onsets, requirement for final codas, etc. Assimilation of major place of articulation of non-adjacent consonants is also unique only in child (e.g., *dog* [gɔg], Pater (2002: 359); also reported in German children, e.g., [po:mas] for [to:mas] *Thomas* [bɛlp] for [gɛlp] *Gelb*, Buckley (2003)). These child-unique phenomena impose a challenge to the *continuity hypothesis*, which states that the acquisition of language is continuous. The hypothesis requires that the grammar of adult and child should have the same formal properties, so child's grammar must be a subset of adult's grammar (Macnamara 1982, Pinker 1984). However, the substantive connection is not maintained in some proposals such as the dual lexicon model which posits separate representations for production and perception (Kiparsky and Menn 1977). Under such model the substantive connection between child and adult grammars is lost (Pater 2002, 2004).

The continuity hypothesis is not a challenge, but is assumed, in Optimality Theory (OT; Prince and Smolensky 1993/2004). Under the OT framework, the same set of constraints are assumed for both children and adults, and phonological acquisition involves learning adults' constraint ranking. In child phonology, due to the lack of production abilities, markedness constraints are ranked higher than relevant faithful constraints (Hayes 2004, Prince and Tesar 2004). I adopt the analysis in Pater (2004) that accounts for the gap between production and perception. Pater (1997b, 2002, 2004) provides Optimality Theoretic analyses for phonological acquisition. In phonological acquisition, it is generally agreed that perception abilities are acquired before production abilities (e.g., Bills and Golston 2002, Hayes 2004). In Pater (2004), it is assumed that a child has representations stored in his/her lexicon, but he/she simply cannot produce them. The acquisition involves two stages of grammars: perception and production. In his analysis, the output of the perception grammar is a stored lexical form, which is in turn the input to the production grammar. The perception grammar gives faithful mappings for the given input, whereas the production grammar yields a mapping which is not faithful to the input, satisfying the markedness constraint. At the adult stage, the markedness constraint that represents child's articulatory limitation is demoted and ranked low. The continuity is maintained in that the same set of markedness constraints are transferred from child to adult stages of grammar. Further details of Pater's analysis will be presented in Section 3.1.

This paper is organized as follows. Section 2 demonstrates the result of the longitudinal case study of a child (Nathaniel). Section 3 provides an OT analysis of the velar fronting and a learning simulation using the GLA. Section 4 is the discussion and Section 5 is the conclusion.

2. A case study

2.1 Listening and transcription procedure

The corpus used for the case study in this paper is a part of CHILDES (Child Language Data Exchange System, MacWhinney 2000). For the longitudinal study I use the data of one boy, Nathaniel (N), a learner of American English. This corpus consists of his dialogues with his father, mother, or an adult in natural, everyday situations such as eating meals and reading books. The period of data gathering is during the ages 2;5.18-3;9.02. Written transcriptions (not phonetic) are provided for all conversations. Audio files are available on the web for some of the dialogues. Among the recordings, eight audio files (shown in (3)) were analyzed in the present paper. The total running time of the recordings under analysis was 187 minutes.

(3) Month of recording	Age	Duration (min:sec)
1979.2	2;5.18	28:51
1979.4	2;8.	33:44
1979.5	2;11.	22:52
1979.9	3;0.19	09:46
1979.11	3;2.24	19:00
1979.12	3;4.09	24:05
1980.1	3;4.17	31:25
1980.5	3;9.02	17:23

The total number of tokens produced by the child in these recordings was 5031. In the present study, target velars were those that appear in syllable onset in strong (stressed or word-initial) position (311 in total). Velars in weak position (non-initial and unstressed) were also examined (80 in total). Velars in coda position were not considered, because VF never occurs in coda.

A preliminary listening of the recordings revealed that velar fronting is observed in the first month in the corpus (2;5.18) but not in the last month (3;9.02). By the age of 3;2.24, most velar fronting instances disappear, so among the available recordings, the ones that approach this age (the closest available were 2;8, 2;11, 3;0.19) were selected for phonetic transcription of the target velars. In addition, the recordings that closely follow the acquisition of velar fronting were transcribed as well (3;4.09 and 3;4.17).

The audio files listed in (3) were downloaded from the CHILDES website (http://childes.psy.cmu.edu/media/Eng-NA-MOR/Snow/) in an mp3 format and transcribed for the velar sounds by the author. The author transcribed the actual pronunciation of velar stops ([k,g]) by listening to the selected audio files on Praat (Boersma and Weenink 2012). The author is a native speaker of Korean, not a native speaker of English. However, the distinction between the velar stops and the coronal stops, which is the concern of this paper, was fairly straightforward in most cases. In the cases where the judgment was unclear, I referred to the formant transitions in the following vowel in order to determine the place of articulation of the consonants, since the second formants (F2) differ by different places of articulation of a consonant and the context vowels (Delattre et al. 1955: 770). Praat was used for inspecting the formant transitions where necessary, which is an obvious advantage using a spoken corpus.

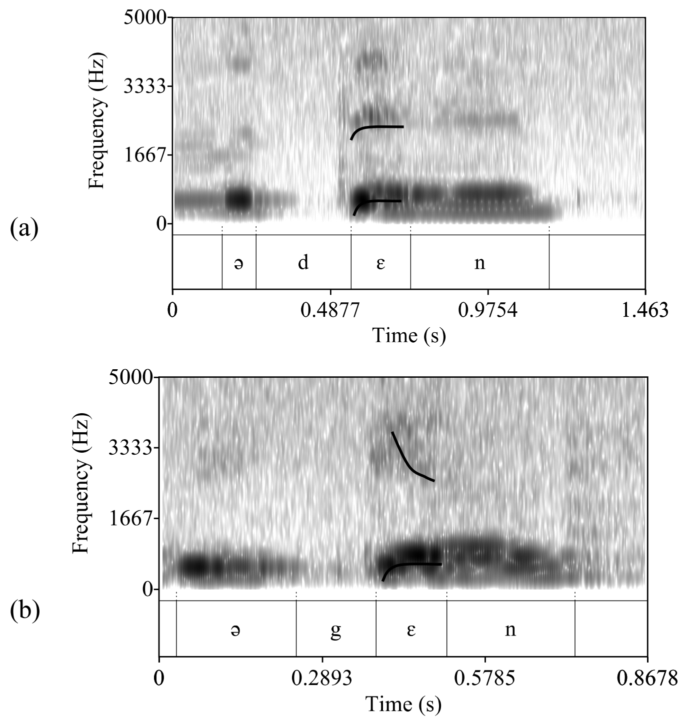

Figure 1. Spectrograms of the utterances of again. (a) Velar fronting: 'Johnny eh marching home again' [əˈdɛn] (2;8), (b) No velar fronting: 'and then we go a bed again' [əˈgɛn] (3;2.24)

Figure 1 shows sample spectrograms of the utterances of *again*, produced at age 2;8 (Figure 1(a)) and at age 3;2.24 (Figure 1(b)). Velar fronting occurred in (a), but not in (b). Formant transitions in (a) shows that this is a coronal stop. The second formant shows a rising transition at the release of the consonant in the context of the vowel [ɛ]. On the other hand, in (b), F2 falls at the beginning of the vowel, suggesting a velar stop (it sounded like a clear [g] though formants somewhat bifurcating). I have examined formant transitions when auditory judgment was unclear, but this was only for a few cases. Formant transitions were often hard to identify and furthermore, it is known that coronals and velars have a similar pattern before back vowels (Delattre et al. 1955: 770, Fig.1). If still unclear from checking F2 transition, those sounds were marked as unidentifiable (4%).

2.2 The results

Velar fronting is frequently observed in earlier ages of this child. The examples in (4) shows examples divided into three stages: (a) velar fronting, (b) variable realization, and (c) velar production in strong position (i.e., acquisition of strong velars). The columns on the left show the realization of target velars in strong positions, and the columns on the right show target velars in weak positions.

(4) a. Velar fronting (2;5.18-2;11)

Strong position		Weak position	
again	[əˈdɛn]	sticky	[ˈtɪki]
sky	[ˈtaɪ]	jingle	[ˈbiə] (deletion)
cold	[ˈtaʊd]	locket	[ˈhaktet] (fronting)
go	[ˈdo]	bicycle	[ˈbaɪsɪtə a] (fronting)
cow	[ˈtaʊ]		
cat	[ˈtæt]		
clock	[ˈtak]		
called	[ˈtaʊd]		
close	[ˈtaʊ]		
gift	[ˈdi:t]		
cream	[ˈti:m]		

b. Variable (2;11-3;2.24. data from 3;0.19)

Strong position		Weak position	
again	[əˈdɛn]	babushka	[ˈbuʃʊka]
go	[ˈdo]		
cake	[ˈkeɪk]		
Katie	[ˈkɪti]		
school	[ˈsku:l]		

c. Acquisition of strong velars (3;2.24 – 3;9.02)

Strong position		Weak position	
go	[go]	Dingo	[dɪŋgo]
again	[əˈgen]	taking	[teɪkɪŋ]
Greg	[grɛg]	sucky	[sʌki]
school	[sku:l]	gargling	[gaglɪŋ]
kangaroo	[kæŋgəru:]		
clock	[klak]		

In (4a), velars in prosodically strong positions (word-initial or stressed position) are pronounced as coronals, as expected. This stage shows many instances of velar fronting in strong position, as illustrated. Weak positions show more variation: target velars are variably realized among velar realization, deletion, or even fronting (i.e., coronal). Deletion of a syllable containing a velar stop is very frequent, probably because unstressed syllables are easily deleted (e.g., Pater 2004: 225). Fronting of velars in weak position is very rare, as expected: *locket* and *bicycle* are the only two instances of coronal in weak position. *locket* [ˈhaktet] may be consonant harmony (assimilated to the following non-adjacent coronal) (Pater 2002: 359ff, Buckley 2003: 4), and the production of *bicycle* was rather unclear. In (4b), the intermediate stage, velar fronting is variable: some undergoes it (*again, go*), others not (*cake, Katie, school*). In (4c), target velars are produced as velars, suggesting that the acquisition of strong velars is completed by 3;2.24.

An orthogonal issue is consonant cluster reduction. It is well-known that consonant clusters are simplified in child language (Pater 2002: 350ff.). The examples in (5) show a part of dialogue containing words that show both cluster reduction and velar fronting. In initial consonant clusters, as *sky* in (5a) and *clock* (5b), fricatives or liquids are deleted in favor of stops. This is due to the preference for a low-sonority sound at the syllable onset (Barlow 1997, Pater 2002: 351). When a consonant cluster contains a velar stop, the retained velar stop undergoes velar fronting (more examples in (4a): *close* [ˈtɑʊ], *cream* [ˈti:m]). In terms of rule ordering, cluster reduction applies first, and then velar fronting applies later (i.e., /skɑɪ/→[kɑɪ]→[tɑɪ]).

(5) a. LIA: snow in the sky.
CHI: sky [tɑɪ] (2;5.18)

b. MOT: oh that's the clocks again.
CHI: clock [tɑk]
CHI: again [əˈdɛn]
MOT: clocks again (2;5.18)

(LIA: an adult, MOT: mother, CHI: child)

Table 1 summarizes the frequencies of the segments that the child produced for target velars in strong (a) and weak (b) positions, arranged according to the age of the child N. In strong position, the majority realization of the target velars is coronal in earlier stages. At the age 3;0.19, velars and coronals have the equal frequency. The majority realization changes to velars after 3;0.19. Consonants other than velars or coronals are also observed, though infrequently, e.g., *cup* [pʌp] (2;5.18), *garbage* [ba:gɪd] (2;8) (labials). By the age of 3;2.24, velar fronting disappeared. In Table 2, the realizations of target velars are further summarized in percentage, summed over each place of articulation ('Velar'=[k,g], 'Coronal'=[t,d], 'Etc.'=others).

Table 1. Production of target velars in strong positions (above) and weak positions (below). '?' indicates unidentifiable production. 'del' indicates deletion.

Age	(a) Strong position									
	k	g	t	d	b	ts	p	?	w	Total
2;5.18		2	20	7			1	2		32
2;8.	3	3	16	17	3			8		50
2;11.	2	1	6	9						18
3;0.19	7			7						14
3;2.24	26	25				1		1	1	54
3;4.09	34	6							1	41
3;4.17	31	14								45
3;9.02	50	6						1		57
Total	153	57	42	40	3	1	1	12	2	311

Age	(b) Weak position								
	k	g	t	d	h	w	del	?	Total
2;5.18	1		2				19	1	23
2;8.	11	5			1		3	3	23
2;11.	3	3							6
3;0.19	1								1
3;2.24	2								2
3;4.09	4	4							8
3;4.17	10	2							12
3;9.02	2	3							5
Total	34	17	2	0	1	0	22	4	80

Table 2. Production of target velars in strong positions (left) and weak positions (right) (%).

	Strong position			Weak position		
	Velar	Coronal	Etc.	Velar	Coronal	Etc.
2;5.18	6	84	9	4	9	87
2;8	12	66	22	70		30
2;11	17	83		100		
3;0.19	50	50		100		
3;2.24	94		6	100		
3;4.09	98		2	100		
3;4.17	100			100		
3;9.02	98		2	100		

The results shown in Table 1 and 2 are plotted in Figure 2 (in percentage), (a) for strong positions and (b) for weak positions. Figure 2(a) shows that in strong positions coronal stops are produced more than velar stops for a velar target by the age 2;11. Velar and coronal stops are equally observed at the age of 3;0.19. After 3;2.24, velar stops are correctly pronounced in strong positions. In earlier stages (2;5.18~2;8), the velars are replaced with sounds other than coronals (indicated as 'Etc.'), and these also disappear together with coronal stops.

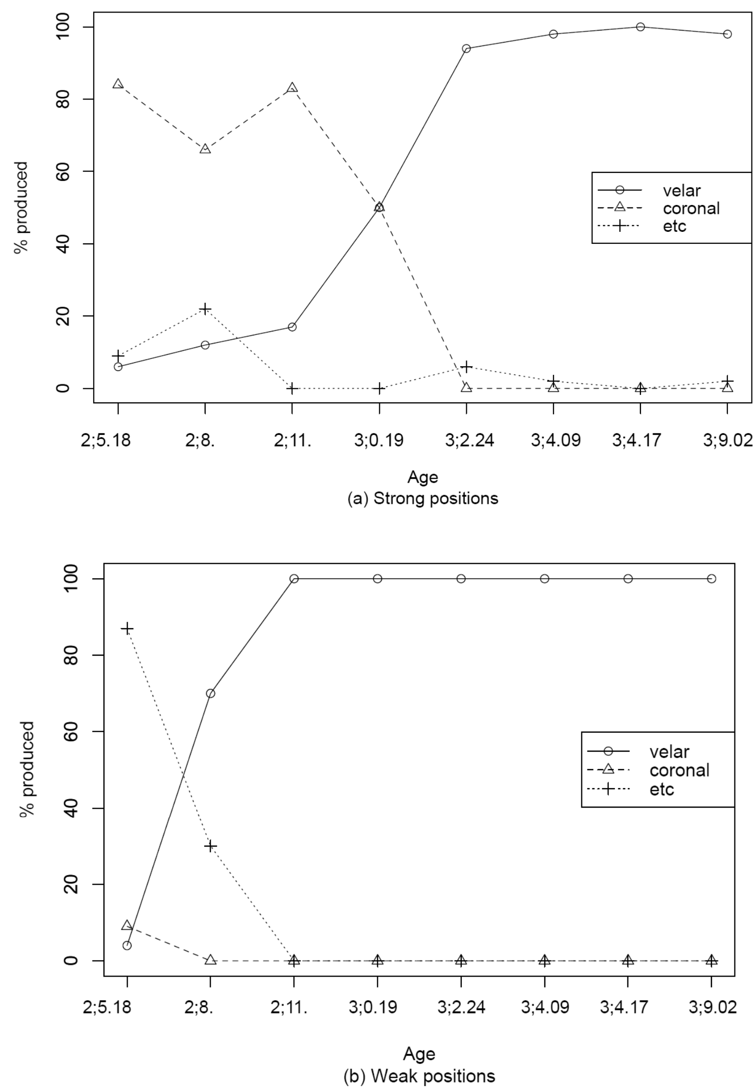

Figure 2. The pronunciation of velar stops in strong (a) and weak (b) positions. The x-axis is the age, the y-axis is the percent pronounced as a particular sound (velars, coronals or others (etc.)).

On the other hand, Figure 2(b) shows the changes in velar production in weak positions. At the age of 2;5.18, the frequencies of both velars and coronals are very low, but 'other' production is the majority, most of which are deletion (19/27=70%). By the age of 2;11, target velars are correctly pronounced in all cases (100%), and by this age the 'etc' production disappears.

We can see that the acquisition of weak velars (2;11) is completed before the acquisition of strong velars (3;2.24). In many cases in early ages the entire unstressed syllables are often omitted, instead of the velar segment alone. In (6a) (unstressed) and (6b) (syllable coda), the velars are produced as velars, i.e., no fronting (syllable codas were not included in the analysis). However, velars in weak positions commonly undergo deletion as in (c) and (d). However, after age 2;11, unstressed syllables are less deleted and target velars in weak position are produced as velars.

(6) a. MOT: that's a label.
MOT: label.
CHI: sticky [ˈtɪki]
MOT: sticky yeah. (2;5.18)
b. CHI: Dada took them off [ˈtʊk] (2;5.18)
c. CHI: jingle bells again. [ˈbiə ˈbaʊ əˈdɛn]
MOT: biobows again?
CHI: this uh this. (2;5.18)
d. MOT: look what's this?
CHI: triangle [tɹɑɪhɑ] (2;5.18)

Note that the increase of velars in strong position follows an approximately S-shaped curve (Figure 2(a)). The rapid increase of velars occurs during a four-month period (2;11-3;2.24). An S-shaped curve suggests that a target is not faithfully realized in the beginning, which is followed by a period of variation, and finally the target is faithfully acquired. An S-shaped trajectory is a common pattern in phonological development (e.g., consonant harmony, Becker and Tessier 2011: 168). Our results show that learning of strong velar production is not immediate. Though the development is not a steady (linear) increase during the whole period of learning, the transition is gradual in the sense that it is not immediate as the CDA would predict. This supports the Gradual Learning Algorithm (GLA) (Boersma and Hayes 2001). In the GLA, accumulation of positive evidence gradually leads to changes in ranking values of relevant constraints. Our results do not support the Constraint Demotion Algorithm (CDA) (Tesar and Smolensky 1998), which predicts that constraint demotion will be immediate as soon as errors are encountered under the current grammar (see Pater 2004: 232 for the same point). Furthermore, the CDA does not account for a variable stage as found in our data, which is aptly modeled by the GLA.

3. Optimality Theoretic analysis

3.1 The gap between perception and production

The errors in child language may arise from two possible sources: limitations in perception or those in production. A child may misperceive adults' pronunciation and store an incorrect lexical form. In this case there is no perception-production gap. Alternatively, a child perceives adults' form correctly (Bills and Golston 2002) but cannot produce it as adults do because of physiological/articulatory limitations. According to Pater (2004: 228-9, 232), these come in two stages, one after the other. In the first stage, perception is limited, and production is also limited because of the misperception. That is, production errors occur because the perceived form is incorrect. In the next stage, perception is overcome but production is still limited due to the less developed vocal organs, even though a child has a correct adult form in the mental lexicon.

The analysis in this section applies to the latter stage where there is a perception-production mismatch. In the previous example (6c), repeated here in (7), the child pronounces *jingle bells* as [ˈbiə ˈbaʊ]. His mother does not understand this and asks using this phonetic form. However, the child knows that the adult form [ˈbiəˈbaʊ] is not *jingle bells*.

(7) CHI: jingle bells again. [ˈbiə ˈbaʊ əˈdɛn]
MOT: biobows again?
CHI: this uh this. (2;5.18)

This short dialogue can be a small piece of evidence that the child has a lexical form close to adults' (at least, the stored form is not the way he pronounces it), but he cannot produce it correctly. Considering (7), it can be suggested that the child under analysis is in the stage where there is a perception-production gap. Thus I adopt a framework that accounts for the gap between perception and production.

Pater (2004) provides a constraint-based analysis that accounts for the discrepancy between perception and production in child phonology. He argues that acquisition of a grammar is not monolithic, i.e., what is perceived is not directly led into production, but it undergoes two stages as shown in (8), an illustration with *garage* [gərádʒ] (Pater 2004: 228).

(8) Perceived form — Stored form — Produced form
gərádʒ → Grammar → gərádʒ → Grammar → gərádʒ

In the first stage, the grammar connects a perceived form to a stored form, which corresponds to the perception stage. In the second stage, a stored form becomes a produced form, which corresponds to the production stage. In child language, *garage* [gərádʒ] is reduced as [gádʒ]. This is due to a requirement for a minimal word size (the ideal trochee), according to Pater

(2004: 225). Suppose a learning stage when a child can correctly perceive the word *garage* as [gərádʒ], but produces it as [gádʒ]. For this reduced form, Pater illustrates the perception and the production grammar as follows (Pater 2004: 230-231).

Pater uses two levels of faithfulness constraints. The perception grammar maps a surface form (S) (=perceived form) into a lexical form (L) (=stored form) whereas the production grammar maps a lexical form (L) (=stored form) into a surface form (S) (=produced form). For the [gərádʒ] → [gádʒ] mapping, a violated faithfulness constraint is MAX, so we have the following two constraints.

(9) MAX(LS): If the input is a lexical form, every segment of the input has a correspondent in the output
MAX(SL): If the input is a surface form, every segment of the input has a correspondent in the output Pater (2004: 230)

The reduced form is due to the requirement for a minimal word size (the ideal trochee, i.e., disyllabic foot), embodied as a markedness constraint WORDSIZE. Using these constraints, the perception of this child is analyzed as in (10) (2004: 231).

(10) Perception

S: gərádʒ	MAX(SL)	WORDSIZE	MAX(LS)
L_1 gádʒ	**!		
☞ L_2 gərádʒ		*	

S is a perceived surface form, L is a stored lexical form. The undominated constraint MAX(SL) penalizes any segments that are deleted from the perceived form, so candidate L_1 is ruled out. Candidate L_2 violates WORDSIZE, but it is the winner because it satisfies MAX(SL). Thus, with this grammar the child stores the form that is faithful to the perceived surface form. MAX(LS) is not applicable because the input is a surface form (S), not a lexical form (L).

In the production grammar, the constraint ranking is the same, but the input is now a stored form (L). In tableau (11), undominated MAX(SL) is vacuously satisfied, because the input is not a surface form. Candidate S_2 is ruled out due to the violation of WORDSIZE. S_1 is the winner despite the violation of MAX(LS) because it satisfies the higher ranked markedness constraint. Thus the child produces a reduced form, though he/she has a correct mental representation.

(11) Production

L: gərádʒ	MAX(SL)	WORDSIZE	MAX(LS)
☞ S_1 gádʒ			**
S_2 gərádʒ		*!	

Tableau in (12) shows the adults' production grammar. The faithfulness constraint MAX(LS) is reranked above the markedness constraint WORDSIZE. With both faithfulness constraints ranked above WORDSIZE, S_2 now becomes the winner, reflecting the adult pronunciation.

(12) Adult production

L: gərádʒ	MAX(SL)	MAX(LS)	WORDSIZE
S1 gádʒ		**!	
☞ S2 gərádʒ			*

3.2 Analysis of velar fronting

The schema introduced in Section 3.1 is used for the constraint-based analysis of velar fronting in child phonology. Since velar fronting involves a change in the place of articulation, a pair of IDENT constraints is used, as presented in (13), instead of MAX constraints.

(13) a. IDENT-PLACE(LS)
If the input is a lexical form, every consonant of the input must be faithful to the place of articulation of the corresponding consonant in the output.
b. IDENT-PLACE(SL)
If the input is a surface form, every consonant of the input must be faithful to the place of articulation of the corresponding consonant in the output.

The relevant markedness constraint that triggers velar fronting is stated as in (14). This constraint bans velar stops occurring in prosodically strong positions (word-initial or stressed syllables). This constraint embodies child's difficulty in producing velar stops in prosodically strong positions, due to the child's characteristic shape of the vocal tract (short palate and relatively large tongue).

(14) *STRONGVELAR: Velar stops cannot be produced in strong position.

In our corpus, the word *again* appears several times over the period under study. Velar fronting is observed in the stressed second syllable in this word until the age of 3;0.19, as illustrated in (15a-c). By the age of 3;2.24, velar fronting disappears, as in (15d). I will illustrate an OT analysis with *again*.

(15) a. Jingle bells *again*. [əˈdɛn] (2;5.18) (all 7 instances)
b. Johnny eh marching home *again* [əˈdɛn] (2;8)
c. Will do dancing and singing *again* in the television? [əˈdɛn] (3;0.19)
d. And then we go a bed *again* [əˈgɛn] (3;2.24)

The ranking in (16) accounts for the gap between perception and production in velar fronting. In the perception stage, the perceived surface form *again* /əˈgɛn/ is faithfully stored as /əˈgɛn/ in the child's lexicon. This is the surface form (the input) shown in the tableau (17). Candidate L_1 is the winner because it satisfies the highest ranked IDENT-PLACE(SL), despite the violation of *STRONGVELAR. Candidate L_2 is ruled out because the place of articulation of the stressed syllable onset differs from the input. With this grammar, the stored lexical form is thus identical to the adult form.

(16) IDENT-PLACE(SL) >> *STRONGVELAR >> IDENT-PLACE(LS)

(17) Perception

S: əˈgɛn	IDENT-PLACE(SL)	*STRONGVELAR	IDENT-PLACE(LS)
☞ L_1 əˈgɛn		*	
L_2 əˈdɛn	*!		

Let us now consider what the grammar in (16) yields as an output for the production stage. In production, we see that *again* /əˈgɛn/ surface as [əˈdɛn] until the age of 3;0.19. IDENT-PLACE(SL) does not apply, and thus the candidate that violates the markedness constraint (S_1) is ruled out, as in (18). Candidate S_2 becomes the winner despite the violation of IDENT-PLACE(LS).

(18) Production

L: əˈgɛn	IDENT-PLACE(SL)	*STRONGVELAR	IDENT-PLACE(LS)
S_1 əˈgɛn		*!	
☞ S_2 əˈdɛn			*

During the period of variation (2;11-3;2.24), *STRONGVELAR is demoted so that it has the same ranking as the competing faithfulness constraint, IDENT-PLACE (LS). Thus, the grammar now selects both candidate forms as possible outputs, as in (19).

(19) Production - Variation

L: əˈgɛn	IDENT-PLACE(SL)	*STRONGVELAR	IDENT-PLACE(LS)
☞ S_1 əˈgɛn		*	
☞ S_2 əˈdɛn			*

By the age of 3;2.24, velar fronting is not observed any more. The child has acquired the production of velars in strong position as adults. At this stage *STRONGVELAR is further demoted below IDENT-PLACE(LS), as in (20). The markedness constraint is ranked low and inactive, reflecting the fact that adults can pronounce strong velars.

(20) Adult production

L: əˈgɛn	IDENT-PLACE(SL)	IDENT-PLACE(LS)	*STRONGVELAR
☞ S_1 əˈgɛn			*
S_2 əˈdɛn		*!	

In tableau (20), candidate S_1 is the winner because it satisfies the faithfulness constraint which is now higher ranked. The perception-production gap, which has once existed in child language, disappears in adult language due to the demotion of the markedness constraint. The child N has acquired the adult grammar for velar production by the age of 3;2.24. (21) summarizes constraint rankings for the period under study.

(21) a. Velar fronting (2;5.18-2;11)
IDENT-PLACE(SL) >> *STRONGVELAR >> IDENT-PLACE(LS)
b. Variation (2;11-3;2.24)
IDENT-PLACE(SL) >> *STRONGVELAR, IDENT-PLACE(LS)
c. Velar production (3;2.24 – 3;9.02)
IDENT-PLACE(SL) >> IDENT-PLACE(LS) >> *STRONGVELAR

3.3 Learning OT grammar of velar production

A learning simulation is conducted in order to test the schematic OT grammar in Section 3.2 (21) with the corpus data. As mentioned, the Gradual Learning Algorithm (GLA) is more realistic as a model of acquisition of velar production. Praat (Boersma and Weenink 2012) is used for the learning simulation. Only two constraints, *STRONGVELAR and IDENT-PLACE(LS) are included in the learning simulation, because IDENT-PLACE(SL) is irrelevant and vacuously satisfied in the production stage. Thus the learned grammar explains only the production side of the grammar.

At the initial stage, the two constraints were assigned the same ranking values, set to 100. The learning settings in Praat were as follows: evaluation noise (2.0), initial plasticity (1.0), replications per plasticity (10000), plasticity decrement (1), number of plasticities (1), Rel. plasticity spreading (0), following a guideline by Pater (2009). The initial OT grammar was fed by a set of frequencies (% values) of velars and coronals at each age (e.g., velars 6, coronals 84 at 2;5.18; velars 12, coronals 66 at 2;8, etc. (See Table 2. ‘etc’s were ignored. Only the proportion between velars and coronals matter)). As shown in Section 2.2, we had eight points in age (from 2;5.18 to 3;9.02). The initial grammar changes according to the learning data over the course of time.

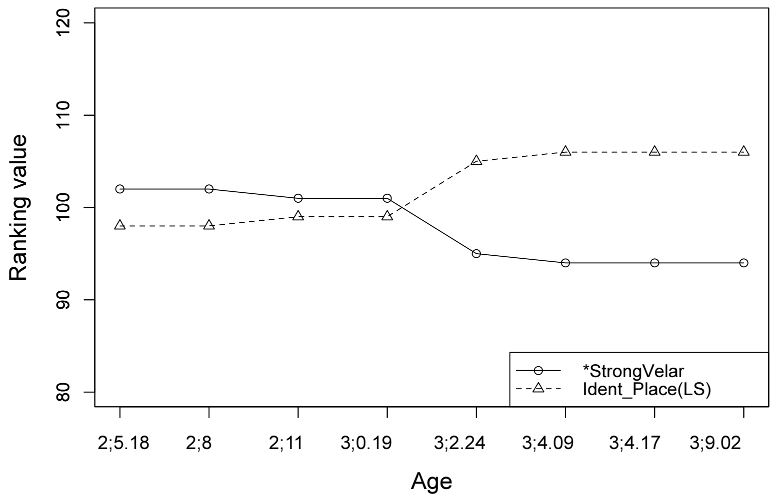

Figure 3. The trajectories of ranking values of the two constraints, *StrongVelar and Ident-Place(LS) over the learning period.

Figure 3 shows the results of the learning simulation. It shows the changes in ranking values of the two constraints over time. In the beginning, *StrongVelar started with a higher ranking value than Ident-Place(LS), reflecting child's articulatory limitation. As time passes, the ranking values of the two constraints become closer to each other. In the previous Figure 2, the number of velars slowly increased until the age 2;11. At 2;11, variability increased (Figure 2), so the ranking values get closer (Figure 3) (the closer the ranking values, the more likely the variation). By 3;0.19, the ranking values remain close to each other, reflecting the variation stage. With more instances of velar realization of target velars fed to the learner, the ranking values of the two constraints are reversed by the age of 3;2.24. At 3;4.09, the difference becomes slightly greater, after which the ranking values stay the same and remain stable.

4. Discussion: the continuity hypothesis and markedness constraints[1]

It should be noted that the constraint *StrongVelar poses a problem in the continuity hypothesis, where it is assumed that children and adults share the same set of constraints. As noted, a markedness constraint *StrongVelar embodies child's articulatory difficulty due to the characteristics of their vocal organs. It may be the case that this constraint should entirely disappear

[1] I thank the anonymous reviewers who pointed out the issues discussed in this section.

as a child grows, instead of being demoted as (21) shows. If the constraint still exists in adults' grammar, there should be a language which shows velar fronting as in child language, which is the basic consequence of having the constraint *StrongVelar. However, this is not the case. This means that *StrongVelar is not just low-ranked in adult grammar, but it should be inactive. In standard OT, there is no mechanism to make a constraint completely inactive – i.e., the effect of the lowest-ranked markedness constraint can emerge under a certain cases (emergence of the unmarked). To avoid this problem *StrongVelar should disappear as a child acquires an adult grammar. Currently, to my knowledge, no OT theories or grammar learning models offer a formal mechanism that *deletes* a constraint, so I leave this as a further research problem. Nevertheless, it would not be surprising if child and adult had different sets of markedness constraints (cf. Markedness can be language-specific, Hume (2003)). In the study of child phonology, it has been argued that children induce their own sets of markedness constraint (e.g., Pater 1997a).

One of the basic tenets of OT is that markedness constraints are innate, shared universally because adults have a similar shape of vocal apparatus. However, if sharing the same vocal organ is the condition for universal markedness, markedness constraints may depend on the group of people who share a similar shape of the vocal organs. That is, the set of markedness constraints may differ in child and in adult, because they have differences in the structure of vocal organs (i.e., relative size of tongue and oral cavity). This is clearly a problem to the continuity hypothesis because this implies that perhaps some markedness constraints should not be transferred from child to adult grammar. Yet, still a great number of markedness constraints should be transferred to adult stage. Such constraints include WordSize in Pater (2004), or *Complex-Ons in Pater (2002), which are typologically attested in both child and adult languages. Thus, the continuity hypothesis cannot be discarded entirely. We can minimally modify the hypothesis saying that most of the constraints are shared by child and adult, except those that address child's articulatory difficulties which are limited only to the children's developmental stage.

It should also be noted that some fixed rankings in adult language can be different in child language, while some others can be shared. As mentioned in the Introduction, child language exhibits peculiar processes that are never found in adult systems (Buckley 2003). For example, child language exhibits less contrasts in onset position than in coda position (Buckley 2003: 3). VF is one of such cases – place contrast is neutralized in onsets in prosodically strong positions ([cor]~[dor] → [dor]), but not in codas. In adult language, onset is the place of contrast, whereas coda is the place of neutralization, so a fixed ranking Ident(Place)_Onset >> Ident(Place)_Coda holds. This ranking is reversed in child language. On the other hand, some fixed rankings should be transferred from child to adult. For example, the universal scale of places of articulation is known as *[dor]>>*[lab]>>*[cor] (Prince and Smolensky

1993/2004: 198, Hume and Tserdanelis 2002: 8ff., Hume 2003: 5-8). This can remain unchanged from child to adult phonology, given that in the process of velar fronting the more marked [dor] becomes the less marked [cor], but not the opposite way.

5. Conclusion

The present study showed how the frequencies of velar and coronal stops in prosodically strong and weak positions change over the course of the learning period. The study reveals that the correct production of velars in strong position is achieved by the age of 3;2.24 in the case of the child studied. The correct production of strong velars rapidly increases during a four-month period, where there is variation between velar fronting and velar production. The learning follows an S-shaped curve. This supports the Gradual Learning Algorithm for the acquisition of strong velars. The present paper also provided an Optimality Theoretic analysis of the changes of child grammar, using Pater (2004)'s framework. This assumes that there is a developmental stage where there is a gap between production and perception. The learning simulation with the proposed constraint schema was conducted using the Gradual Learning Algorithm. The simulation results show that in the beginning the markedness constraint is higher than the faithfulness constraint. With more data, the ranking values become close to each other, reflecting the variable stage. After that, the faithfulness constraint has a higher ranking value than the markedness constraint, which stays stable, reflecting the completion of acquisition. The results show how rankings of markedness and faithfulness constraints change over time for the acquisition of velar production in a child.

A limitation of the current study is that the results are from only one child. The period of data gathering is also limited, as mentioned, though the transition period was included within the period under study. It would also be interesting to see whether velar fronting is observed in other languages as well. If the articulatory limitations are the only source of velar fronting, it can be predicted that velar fronting would be found universally, since children have the common vocal organs.

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