Learning bias of phonological alternation in children learning English

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Jo, Jinyoung. 2016. Learning bias of phonological alternation in children learning English *SNU Working Papers in English Linguistics and Language 14, 45-81.* It has been assumed that output-to-output faithfulness constraints are undominated in the initial stages of learning (McCarthy, 1998; Hayes, 2004), but they are gradually demoted in the hierarchy as children are increasingly exposed to alternating forms. A prediction ensuing from this claim is that children will initially favor non-alternating forms, but they will eventually produce alternating forms as adults do. This study aims to provide empirical evidence for this claim with the case of American English Flapping. According to Bernhardt and Stemberger (1998), a child learning English did not apply flapping rule where adults do, for the sake of paradigm leveling; for instance, she produced si[t]ing (rather than si[ɾ]ing) for *sitting*, on the model of si[t]. Using six children's longitudinal spontaneous speech recorded from the age of 0;11 to 4;0 (Demuth, Culbertson, & Alter, 2006), this study investigated how children's probability of producing each variant of word-medial /t/ and /d/ changes as a function of age. The results demonstrated that the frequency of the variants that are more faithful to the base (unsuffixed) form, such as si[t]ing, decreases as a function of age, while the frequency of [ɾ] was found to increase over time. The findings indicate that children in fact are biased against alternation, especially in the initial stages of learning. **(Seoul National University)**

Keywords: learning bias, alternation, output-to-output faithfulness constraints, American English Flapping

1. Introduction

Language learners often exhibit biases in learning phonological alternations. Evidence for learning biases among adult learners has been provided in numerous experimental works (e.g., White, 2014; Wilson, 2006). However, few studies have investigated the biases that young learners have when acquiring patterns of alternation. This might be partially because we have little evidence for when children master patterns of alternation. As pointed out in Hayes (2004), a large amount of variation is observed between different morphological processes. Some studies documented quite an early mastery of morphology; it was reported in Aksu-Koç and Slobin (1985) that 15-month-olds learning Turkish were able to use the accusative suffix [-a] ~ [-e] correctly. However, other studies suggest that morphology is learned somewhat later than this. For example, Smith (1973) showed that a English-learning child at age 2; 2 was not able to produce plurals correctly. In Berko's (1958) wug-test, even 4-year-old children failed to generalize the patterns of alternation in English plural suffixes to new items. Another case showing relatively late morphophonemic acquisition is the non-concatenative morphology of Modern Hebrew (Berman, 1985); young learners of Modern Hebrew did not master the patterns of non-concatenative morphology until they were 4-5 years.

Exploring the biases children possess in morphophonemic learning is nevertheless crucial in understanding some aspects of phonological acquisition. More specifically, it might help us provide an explanation for why children systematically make a particular pattern of errors. For instance, children learning Spanish incorrectly generalize diphthongization found in the 1sg, 2sg, 3sg and 3pl to the rest of the forms in a verb paradigm, which are supposed to be realized with non-diphthongized vowels (Clahsen, Aveledo, & Roca, 2002). Similarly, child learners of German used the vowel of infinitive, 1sg, 1pl, 2pl and 3pl forms in place of 2sg and 3sg (Clahsen, Prüfert, Eisenbeiβ, & Cholin, 2002). As will be discussed throughout this paper, these over-regularization patterns observed in the speech of young learners can be attributed to their innate bias towards non-alternation, or paradigm leveling. We can thus achieve deeper understanding of why children produce certain patterns of systematic errors by investigating biases in acquiring alternation.

The present study investigates child learners' bias towards non-alternation, focusing on the case of American English Flapping.

According to Bernhardt and Stemberger (1998), a child beginning to learn English did not apply flapping rule where adults do, for the sake of paradigm leveling; for instance, she produced si[t]ing (rather than si[ɾ]ing) for *sitting*, since flapping would trigger [t] ~ [ɾ] alternation between the base form si[t] and the suffixed form si[ɾ]ing. Based on longitudinal speech data of six child learners of English, this study aims to explore how children's preference for non-alternation changes over time. The results demonstrated that they in fact are biased against alternation, especially at the initial stages of learning. This finding provides empirical support for the claim in McCarthy (1998) and Hayes (2004) that output-to-output faithfulness constraints banning alternation was initially undominated, but later demoted in the learning process.

The rest of the paper is organized as follows. The next section reviews previous research on children's biases in learning alternation. Section 3 describes the method and procedure used in this study. Then the results of the corpus study will be presented in Section 4, which is followed by a formal analysis of the results in Section 5. In Section 6, I present the results of learning simulations employing maximum entropy grammar (Goldwater & Johnson, 2003) to model the children's learning trajectories. Section 7 discusses remaining issues and concludes.

2. Previous studies: biases among children learning alternation

In Optimality Theory (Prince & Smolensky, 1993), it has been assumed that output-to-output faithfulness constraints are ranked high *a priori* by children acquiring language (B. P. Hayes, 2004; McCarthy, 1998). The claim is that OO-faithfulness constraints are undominated at the initial stage of learning, i.e., prior to receiving any input data, and they are gradually demoted in the hierarchy as children are increasingly exposed to alternating forms. A prediction ensuing from this claim is that children will initially favor non-alternating forms, as high-ranked OO-faithfulness constraints require phonological similarity between morphologically related forms, but they will eventually be led to produce alternating forms as adults do. Moreover, assuming that demotion of a constraint is a gradual process, the rate of demotion is determined by the frequency of their violations that young learners encounter. Therefore, if one alternation occurs more frequently than another, the learner is expected to produce it earlier in the learning process.

Some empirical evidence for the initial bias towards non-alternation has been provided in the literature, though the reports have been only anecdotal and sporadic in form. For instance, it was reported in Kazazis (1969) that a 4-year-old learning Modern Greek innovated the illegal sequence *[xe] in producing [ˈe**x**ete] ‘you-pl. have’, the adult form of which is [ˈe**ç**ete], on the model of [ˈe**x**o] ‘I have’. Considering that the child had never found *[xe] in adult speech (as it violates phonotactics of the language), the markedness constraint that bans the sequence should be undominated. However, an OO-faithfulness constraint relevant to [x]/[ç] distinction was ranked even higher than the markedness constraint, leading the child to establish a non-alternating paradigm. A similar case, as already mentioned above, involves American English Flapping; according to Bernhardt & Stemberger (1998), a child learning American English produced [t] or [d], in order to satisfy OO-faithfulness constraints, where adults normally produce [ɾ]. More specifically, the child produced [sɪ**t**ɪŋ] ‘*sitting*’ instead of [sɪ**ɾ**ɪŋ] to base its pronunciation on [sɪ**t**] ‘*sit*’, and in the same way, *needed* was realized as [niː**d**əd] rather than [niː**ɾ**əd] on the model of [niː**d**]. We can infer that [t] and [d] from unsuffixed forms, [sɪt] and [niːd], generalized to the corresponding suffixed forms [sɪtɪŋ] and [niːdəd], respectively. In terms of OT constraints, the avoidance of flaps in [sɪtɪŋ] and [niːdəd] satisfies OO-faithfulness constraints for [voice] and [sonorant]. If the suffixed form of [si**t**] is realized as [sɪ**ɾ**ɪŋ], the [t] ~ [ɾ] alternation between the two output forms violates OO-faithfulness constraints for [voice] and [sonorant][1]. Likewise, when the suffixed form of [niː**d**] is produced as [niː**ɾ**əd], the [d] ~ [ɾ] alternation between the base and its derived counterpart violates OO-faithfulness constraints for [sonorant]. We can thus interpret that the children's tendency to avoid producing flaps in the suffixed forms is due to high-ranking OO-faithfulness constraints.

While these studies do provide evidence for the young learners' bias for non-alternation, they are not sufficient to support the claim in Hayes (2004) and McCarthy (1998) that predicts children's initial preference for non-alternation but an increased probability of producing alternation at later stages of learning. Most importantly, since very few studies investigated how the child learners' probability of producing (non-)alternation changes over time, we lack empirical evidence showing that they indeed demote OO-faithfulness constraints as they become more experienced in learning and increasingly encounter alternating forms along the developmental stages. Furthermore, we should also check whether the observations made in previous studies, most of which are based on only one child, are generalizable to a meaningful number of children. For example, if the occurrence of [t] or [d] in the speech of the child reported in Bernhardt and Stemberger (1998) is attributed to how young children's grammars are constructed, but not some other idiosyncratic characteristics of that particular child's speech, the same tendency should be attested in the speech of every English-learning child. In these respects, we need more extensive research on how children overcome the bias in the process of learning.

Recently, Do (2013) conducted a series of experiments to investigate Korean children's learning trajectories of alternation shown in Korean noun / verb paradigms and modeled the results with maximum entropy grammar. To my knowledge, this is the only study that adequately tested the claim that OO-faithfulness constraints are ranked high *a priori* and

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[1] Throughout this paper, I assume that English flap has [+sonorant] and [+voice] features.

that they are demoted during the learning process. Children aged between 4 and 8 participated, whose patterns of alternation were expected to differ from those of adults. This seems to be a very late acquisition of alternations, which is probably due to a high degree of complexity found in Korean noun / verb paradigms. The results demonstrated that the child speakers inflected nouns and verbs in a way that is faithful to one specific part of the paradigm, therefore satisfying OO-faithfulness constraints.

The present study aims to provide additional empirical evidence for the prior bias towards non-alternation, as claimed in previous studies (Do, 2013; B. P. Hayes, 2004; McCarthy, 1998). More specifically, this study investigates the paradigm leveling case of American English Flapping in child speech as reported in Bernhardt and Stemberger (1998). Using longitudinal speech data of six children learning American English aged approximately between 1 and 4, I examined how the child learners produce /t/ and /d/ for which flapping may apply in principle, but may not be produced as flaps in conformity to paradigm leveling. The results revealed that the frequency of the variants that are more faithful to the base (unsuffixed) form, such as si[t]ing, decreases as a function of age, while the frequency of [ɾ] is shown to increase over time[2]. These findings suggest that OO-faithfulness constraints are undominated in the initial stages of language learning but gradually undergo demotion, as claimed in McCarthy (1998) and Hayes (2004).

Note that the present study investigates biases among very young children. The corpus data utilized in this study (Demuth, Culbertson, & Alter, 2006) contains speech of children younger than four years old. They were younger than the child participants in Do's (2013) experiments, whose age ranged from 4 to 8. Since flapping is a robust pattern of alternation in American English, even young learners might

[2] In this paper, I assume that OO-faithfulness constraints require faithfulness to a base form (Benua, 1997; Kenstowicz, 1997), which is assumed to be the unaffixed form for present purposes. However, I also consider the possibility that the children at certain learning stages might not recognize which form of the paradigm serves as the base.

have acquired the alternation. In addition, the data includes child-directed speech as well (elicited mostly from mothers), the target grammar that the children are supposed to learn. By comparing child's grammar with adult's grammar, we can trace the learning trajectory of how children reach the final stage of learning. We can also explore the potential influence of input on the children's production of /t/ and /d/, looking into the observation made in Bernhardt & Stemberger (1998) in more detail.

3. Methods

3.1 Data

The data examined in this study is the Providence Corpus (Demuth et al., 2006), which consists of audio and video recordings of spontaneous speech interactions between six mother-child dyads. All six children (three boys, three girls) were monolingual speakers of American English. Recording started between the ages of 0;11 and 1;4, when each child began to produce their first words, and ended when they were around 3 or 4 years old. Recordings from four dyads were collected once in every two weeks; the other two had denser corpora, with weekly recordings for approximately a year.

Children's speech across all periods in the corpus was subject to analysis. In this way, the youngest age from which the data were collected was 0;11 and the oldest 4;0. It was necessary to examine if the children produced /t/ or /d/ as flaps (as a result of demotion of the relevant OO-faithfulness constraints) from the very beginning of their learning process. As discussed in the previous section, the rate of demotion of a constraint is determined by the frequency of its violations in the input; since flapping in American English is a widely observed process (Eddington, 2007; Patterson & Connine, 2001) that is found both within a word (e.g., *water*) and across word boundaries (e.g., *a lot of*), children might already have demoted the OO-faithfulness constraints by the time they produced their first words. Meanwhile, it was also necessary to examine whether they actively produced flaps in much later learning stages. The reasons were twofold. First, by examining the probability of producing flaps, we can check whether the OO-faithfulness constraints are demoted or not by that time. If children were more likely to produce flaps for /t/ and /d/ in later stages of learning, we can interpret that it is probably due to demotion of OO-faithfulness constraints. Second, while OO-faithfulness constraints might no longer be active in children's grammar at that time, their production of flaps might still be restricted by articulatory constraints. Findings from previous studies (e.g., Klein & Altman, 2002; Rimac & Smith, 1984) suggested that children may still find it difficult to produce flaps even at around age 4, the oldest age from which recordings were obtained in the data examined in this study. Klein & Altman (2002) showed that children learn to produce flaps gradually and that children as old as 48-60 months still could not produce flaps in an adult-like manner. Rimac & Smith (1984) pointed out that the fast movement of the tongue involved in producing flaps might pose an articulatory challenge for young children, as they speak more slowly than adults, and that even 8-year-olds are still learning to produce flaps. Therefore, children's speech from the entire period in the corpus, i.e., from 1 to 4 years of age, was analyzed.

3.2 Target words

In order to select the words to be examined in this study, I first generated a list in which all the words produced by the six children were presented in descending order of token frequency. Then I manually extracted from the list all the disyllabic words where flapping may apply, i.e., words with an intervocalic /t/ or /d/ followed by an unstressed vowel. The words thus chosen were categorized into four types (see Table 1), i.e., (a) words with an intervocalic /t/ that had a base form (e.g., *eating*, base: *eat*), (b) words with an intervocalic /t/ that had no base form (e.g., *potty*), (c) words with an intervocalic /d/ that had a base form (e.g., *hiding*, base: *hide*), (d) words with an intervocalic /d/ that had no base form (e.g., *ready*). Words of type (a) and (c), i.e., suffixed words, were examined to see if younger children produced variants that are faithful to the base form, e.g., ea[t]ing and hi[d]ing. Words of type (b) and (d) were also examined for comparison, for which flapping may apply but there is no base form where OO-faithfulness constraints can operate. More specifically, if the children's production of hi[d]ing is motivated purely by its phonological resemblance to hi[d]e, *ready* should be produced with a flap since there is no reason for them to pronounce it with [d]. However, if hi[d]ing arises simply due to articulatory difficulties in producing flaps, *hiding* and *ready* should be realized with a similar proportion of [d]. Yet another possibility is that both factors, i.e., maintaining phonological similarity to the base and articulatory constraints, can have an effect. In this case, [d] will occur in both *hiding* and *ready*, but its occurrence should be somehow more robust in *hiding*.

For type (a) and (c), words with a reasonably high token frequency were chosen for analysis, i.e., higher than 20. For words of type (b) and (d), an attempt was made to select items whose token frequencies roughly matched those of words in (a) and (c), respectively. Previous studies suggest that token frequency might affect the probability of occurrence of a flap in word-medial position; for example, Patterson & Connine (2001) found that flapping was predominant in high frequency words with medial /t/, whereas low frequency words showed less frequent occurrence of flaps. (Realization of medial /d/ was not investigated in this study.) However, due to paucity of disyllabic words with medial /d/, the token frequencies of words in (c) and (d) do not match closely. The list of words finally selected for analysis is given in Table 1.

Table 1. The target words examined for realization of /t/ or /d/. The numbers in CHI (child) and MOT (mother) columns indicate token

frequency of each word. When caculating frequecy presented here, tokens were excluded that were not coded for reasons to be explained in 3.3, e.g., due to poor recording quality.

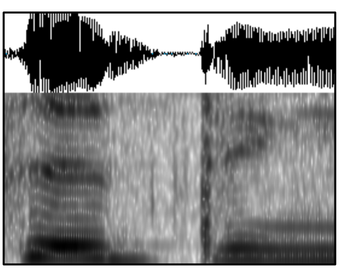
VtV					
Base: O			**Base: X**		
	CHI	**MOT**		**CHI**	**MOT**
eating	173	618	potty	125	346
sitting	108	337	better	108	630
getting	108	541			
putting	105	334			
Total	494	1830	total	233	976
VdV					
Base: O			**Base: X**		
	CHI	**MOT**		**CHI**	**MOT**
birdy	73	104	ready	182	1239
hiding	66	251	teddy	26	138
reading	31	193	ladder	25	62
total	170	548	total	233	1439

As mentioned earlier, mothers' production of the target words was also examined. A reasonably large number of tokens (approximately 20 percent of the total) from mothers' production were coded. Care was taken in making the sample dataset so that about the same number of tokens were selected from each speaker and each word, and they were populated evenly across the children's ages. In this way, the sample could adequately represent the entire data.

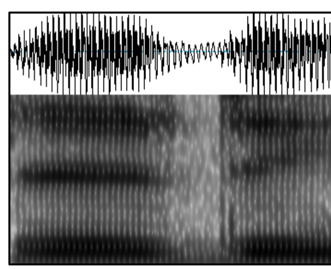
3.3 Coding

Realization of word-medial intervocalic /t/ was coded for [t], [d], [ɾ] or some other variants. In order to determine whether /t/ or /d/ was flapped or not, I primarily coded the tokens perceptually. As pointed out in Song, Shattuck-Hufnagel, & Demuth (2015), since acoustic characteristics of flaps have not been fully agreed upon in the literature, it is not an easy task to determine the occurrence of flaps acoustically. Also, it was found in de Jong (1998) that perceptual transcription of the presence/absence of flaps was quite consistent among the transcribers, suggesting that perceptual coding is moderately reliable.

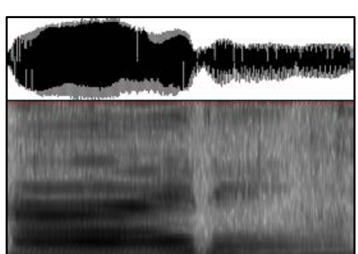
Figure 1. Representative waveform and spectrogram for [t], [d] and [ɾ]. For each token, only some portion of the entire image was presented here due to space limits of this paper.



a. [t] (*sitting*)



b. [d] (*sitting*)



c. [ɾ] (*hiding*)

However, determining presence/absence of flaps based only on perception may be somewhat limited. Therefore, acoustic cues were also consulted. De Jong (1998) argued that the clearest acoustic cues to a perceived flap were the presence of voicing in the closure and the lack of a salient release burst. Figure 1c shows an example of /d/ coded as a flap. When such acoustic evidence was found, the token was coded as flapped. In coding the stops, I primarily relied on acoustic cues. When the release of an oral occlusion was observed, often signaled by vertical spikes in the waveform and the spectrogram, the token was coded as a stop, i.e., either [t] or [d]. If there was evidence of voicing during the consonant closure, signaled by a voice bar, the token was coded as [d] (see Figure 1b). Otherwise, the token was coded as [t] (see Figure 1a).
Tokens were discarded when the child's speech was unrecognizable due to a significant overlap with background noise or mother's speech, when the child's voice was not loud enough, or when the recording quality was poor due to equipment failure.

4. Results

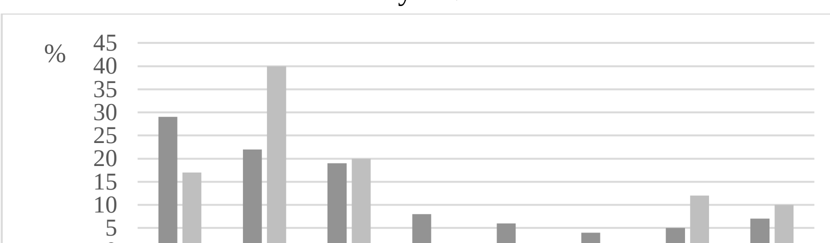
In this section, the observed frequencies of the variants of /t/ and /d/ in children's speech are first reported. The results of the coding for /t/ and /d/ will be presented separately, and within each consonantal condition, suffixed words (e.g., *eating*) and words with no base form (e.g., *potty*) are compared in terms of how /t/ or /d/ were phonetically realized in each context. Then the observed frequencies of the variants in mothers' production are also presented in the same way.

4.1 Children's production of intervocalic /t/ and /d/

4.1.1 Realization of intervocalic /t/ in child speech

Figure 2 shows the attested variants of /t/ in suffixed words (*eating* words) and words which have no base form (*potty* words) produced by children. The first thing to examine is whether children actually produced variants in *eating* words that are more or less faithful to the base form (e.g., ea[t]). Observed frequencies of each variant were compared between *eating* and *potty* words, in order to verify that production of variants in *eating* words that are faithful to the base is indeed motivated by OO-faithfulness constraints. As the total number of tokens examined were different for *eating* and *potty* words, comparisons were made in terms of the percentage of tokens coded as each variant out of all tokens analyzed, rather than raw frequency of each variant.

Figure 2. Attested variants of intervocalic /t/ in *eating* and *potty* words in child speech. The numbers indicate the percentage of tokens coded as each variant out of all tokens analyzed.



	ɾ	d	Ø	t	n	ʔ	others	excluded
eating	29	22	19	8	6	4	5	7
potty	17	40	20	0	1	0.5	12	10

Most importantly, only *eating* words showed [t] variants. Assuming that their base forms such as *eat* are realized with [t], this result can be interpreted as reflecting the children's tendency to base their pronunciation of *eating* words on that of their base forms. In other words, since *potty* has no base form to resemble, the reason why [t] variants were attested only in *eating* words is probably due to their phonological resemblance to their base forms, enforced by OO-faithfulness constraints. In order to test the claim in McCarthy (1998) and Hayes (1994), i.e., OO-faithfulness constraints are high-ranked *a priori* but demoted in the learning process, it was necessary to check whether [t] is attested only at the beginning stages of learning. Figure 3 shows the distribution of the four variants that are most frequently attested, i.e., [ɾ], [d], [Ø] and [t], across children's age in days.

Figure 3. Distribution of [d], [Ø], [ɾ] and [t] in *eating* words across children's age (in days)

Note that [t] was attested only at the early stages of learning, roughly before the age of 750 days. This finding supports the claim that OO-faithfulness constraints, requiring the realization of /t/ in *eating* words to be similar to [t] in their base words, are high-ranked only in the initial stages of learning.

Distribution of [d] and [ɾ] also merits discussion. As shown in the first and the third panel in Figure 3, children tended to produce [d] more frequently in earlier days, while they produced [ɾ] more frequently in later stages. One possible explanation for the distribution of [d] and [ɾ] for *eating* words is that it is difficult for children to properly articulate flaps and that they instead choose to produce [d]. It was pointed out in many previous studies that flaps might be hard for young learners to produce due to their articulatory constraints and that they most often produce [d] where adults produce flaps (Klein & Altman, 2002; Rimac & Smith, 1984). In this sense, the reason why their pronunciation moves from [d] toward [ɾ] is because as they become more experienced learners, they have a better command of articulatory systems.

An alternative explanation is based on the idea that one OO-faithfulness constraint might be demoted faster than another. Consider first that [d] as a realization of /t/ in *eating* words violates OO-faithfulness constraint for [voice], while [ɾ] violates OO-faithfulness for both [voice] and [sonorant]:

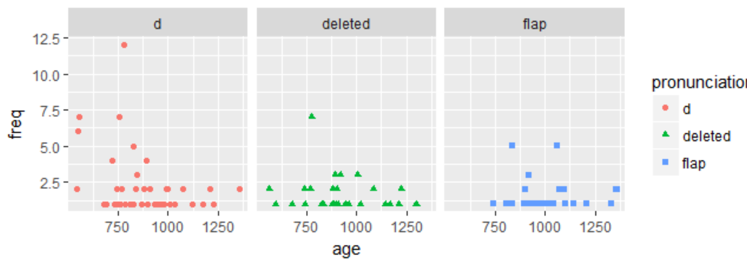
(1) Violation of OO-faithfulness constraints by [t], [d] and [ɾ] variants

/iːtɪŋ/ base: [iːt]	ID-OO(son)	ID-OO(voi)
iːtɪŋ		
iːdɪŋ		*
iːɾɪŋ	*	*

If we assume that ID-OO(voi) is demoted earlier than ID-OO(son), there must be a learning stage where only ID-OO(son) is undominated. At this point, [ɾ] cannot occur as it fatally violates high-ranked ID-OO(son), while [d] might be able to occur (unless ruled out by some other constraints). Assuming constraints are assigned numerical weights, the different rate of demotion between ID-OO(voi) and ID-OO(son) can account for the fact that [d] variants were more likely to appear in the earlier periods, and [ɾ] variants were more likely to be observed in later periods.

In order to test these two hypotheses, i.e., articulatory reasons and varying rates of demotion among different constraints, it was necessary to investigate the frequency of [d] and [ɾ] in *potty* words. Figure 4 shows the distribution of the three variants that are most frequently attested, i.e., [ɾ], [d] and [Ø], as a function of children's age in days.

Figure 4. Distribution of [d], [Ø] and [ɾ] in *potty* words across children's age (in days)



Note that the same tendency was observed in *potty* words as well, i.e., [d] variants were more frequently observed in the earlier stages while [ɾ] variants were more frequently attested somewhat later. The first hypothesis is thus supported. Because *potty* words have no morphologically related forms, there is no way that the OO-faithfulness constraints can operate to prefer [d] to [ɾ]. Clearly, it is likely that children found it challenging to produce a flap and their articulatory constraints enforced [d] as an alternative pronunciation.

We have seen that children produce [d] instead of [ɾ] due to articulatory reasons. But we should also ask if the second hypothesis, i.e., earlier demotion of ID-OO(voi) than ID-OO(son), can also contribute to explaining why children first produce [d] and then only later produce [ɾ] in *eating* words. This explanation does not seem to hold; if the difference in rate of demotion is also in effect, such tendency should be more robust in *eating* words than in *potty* words. Specifically, if *eating* words are affected by OO-faithfulness constraints in addition to the articulatory factors, the probability of producing [d] in *eating* words should be higher than *potty* words, where only the latter factor is at work. The opposite is true, however. Surprisingly, as seen in Figure 2, /t/ was more frequently realized as [ɾ] than [d] for *eating* words, while it was more frequently realized as [d] than [ɾ] for *potty* words. For now, I do not have an explanation for why the ratio of [d] to [ɾ] should be higher in *potty* words. It might have been the case that *eating* words happened to be extracted from later stages than *potty* words, when the children had a better command of their articulatory systems and therefore were more likely to produce flaps. I also considered the possibility that the frequency of *eating* words was higher than *potty* words, either in children's speech or in mothers', as previous studies found that /t/ in words with higher frequency were more likely to undergo flapping (Patterson & Connine, 2001). This does not seem to be the case, however. The mean token frequency of *eating* and *potty* words in children's speech was 123.5 and 116.5, respectively. Although the token frequency was higher in *eating* words, the difference does not seem to be large enough to have influenced their probability of being produced with flaps. In mother's speech, the mean token frequency of *eating* was rather lower (457.5) than that of *potty* words (488). Therefore, I reject the possibility that token frequency might have affected the probability of /t/ being realized as flaps in *eating* and *potty* words.

Despite some challenges in interpreting the results, one thing that is clear in comparison between *eating* and *potty* words is that [t] variants, which is maximally faithful to the base forms (e.g., ea[t]), were only attested in *eating* words. I argue that this is due to OO-faithfulness constraints that require phonological identity between morphologically related words. One might wonder if such result is due to the influence of input; it could be the case that mothers also produced a small amount of [t] variants for some reason, and children just mimicked the pattern observed in the input. I consider this possibility in section 4.2.

4.1.2 Realization of intervocalic /d/ in child speech

Based on the findings reported in the previous section, a couple of predictions can be made regarding the children's production of /d/ in suffixed words (*hiding* words) and in words with no base form (*ready* words). First, the articulatory challenges involved in producing flaps will lead the children to produce [d] more frequently during the early stages of learning. As they become experienced learners, however, the frequency of [d] will decrease and the probability of producing flaps will increase over time. This holds true for both *hiding* and *ready* words. As shown in Figure 6 and Figure 7, the prediction was upheld; children were more likely to produce [d] in earlier stages, and flaps in later stages of learning.

More importantly, the occurrence of [d] should be more prevalent in *hiding* words than *ready* words, since *hiding* words are additionally regulated by OO-faithfulness constraints that demand for phonological resemblance between a base form (e.g., hi[d]e) and its suffixed counterpart (e.g., hi[d]ing). This prediction was born out as well. Figure 5 presents the frequency of variants of /d/ in *hiding* words and *ready* words observed in children's speech. Note that /d/ in *hiding* words was more frequently realized as [d] than [ɾ] (36% vs. 16%), while in *ready* words /d/ was more frequently realized as [ɾ] than [d] (36% vs. 20%). I suggest that the ratio of [d] to [ɾ] is higher in *hiding* words because the probability of producing [d] in these words are enhanced by both articulatory and grammatical factors.

Figure 5. Attested variants of intervocalic /d/ in *hiding* and *ready* words in child speech. The numbers indicate the percentage of tokens coded as each variant out of all tokens analyzed.

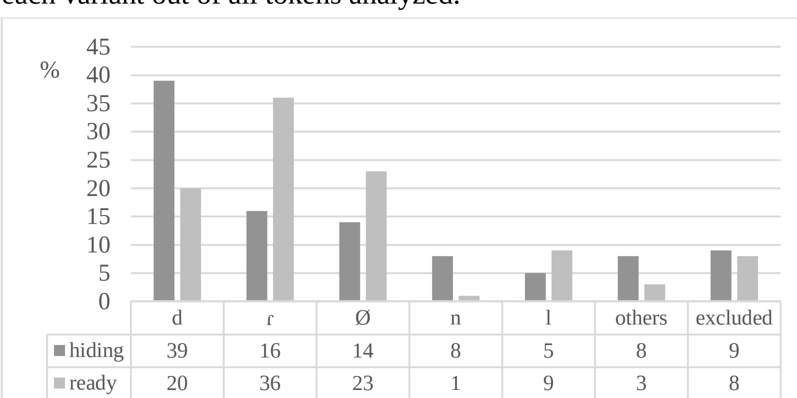


Figure 6. Distribution of [d], [Ø] and [ɾ] in *hiding* words across children's age (in days)

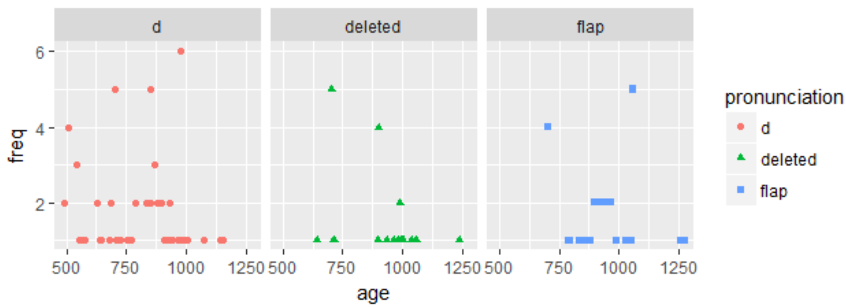
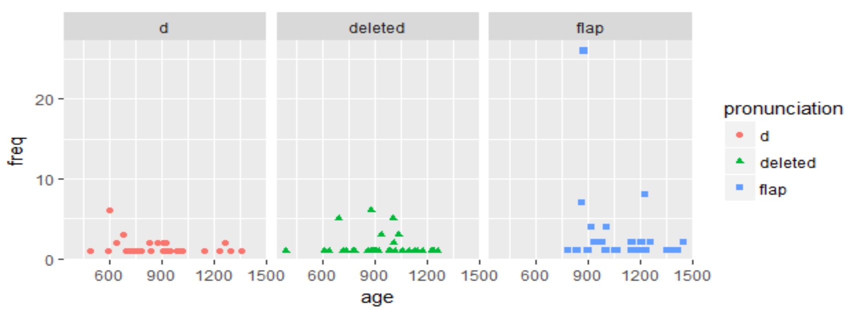


Figure 7. Distribution of [d], [Ø] and [ɾ] in *ready* words across children's age (in days)



There is yet another piece of evidence that OO-faithfulness constraints are actually in effect, which will become clearer in Section 4.1.4. When we take a closer look at the attested learning trajectories, we can notice that the dominance of [d] over [ɾ] in terms of frequency persists for a longer period of time in *hiding* words than for *ready* words. Articulatory factors alone cannot explain why such difference arises, since they are supposed to influence both *hiding* and *ready* words.

To summarize, we can infer from the attested variants of /d/ that children do produce suffixed words that are phonologically similar to their base forms. The question we must ask at this point is whether there is evidence for the demotion of OO-faithfulness constraints. As will be discussed in Section 4.1.4, there are reasons to believe that OO-faithfulness constraints are in fact demoted. But before I report the attested learning trajectories in Section 4.1.4, I briefly comment on the assumption in this study that the base form is the unsuffixed words, i.e., *eat* and *hide*, and that they are produced with [t] and [d], respectively.

4.1.3 Is ea[t] really the base?

I have assumed so far that among morphologically related forms, the unsuffixed forms serve as the base. However, this might not be the case for children at a very young age. That is, child learners at the very beginning stage of learning might not be able to recognize which form of the paradigm serves as the base. For example, it is possible for child speakers to regard *eating* as the base rather than *eat*. In that case, phonetic realization of /t/ in *eat* would be required to resemble that of /t/ in *eating*, which is either [d] or [ɾ] in the majority of cases. In order to test this possibility, we must examine if /t/ in *eat* is realized as such variants as well.

It is also possible that children might not even possess the notion of base and therefore treat *eating* and *eat* equally. In that case, children would simply mimic the relative frequencies of the attested variants shown in the input when producing *eating*. Since flapping is the dominant pattern for adults speaking American English (Eddington, 2007; Patterson & Connine, 2001), *eating* words are most often produced with a flap (see Section 4.2.) It follows that children would also produce flaps with a high frequency in the earliest stages of learning when they do not have the ability for morphological parsing. As shown in Figure 3, *eating* words were in fact realized with flaps in very early stages, but this finding is not enough to support the claim that children mimics the variants observed in the input. This is because such mimicking was not attested in *hiding* words, for which flaps were not observed until the age of approximately 750 days.[3] More research is needed to figure out at which point in learning processes children learn how to correctly perform morphological parsing.

Problems still arise even if we do assume that children consider unsuffixed forms as the base. I have assumed so far that the observed variants of [t] in *eating* words and [d] in *hiding* words were modeled on [t] and [d] in the corresponding base forms, e.g., *eat* and *hide*, respectively. However, it is worth examining if *eat* and *hide* words are actually produced with 'canonical' variants of [t] and [d], i.e., with a clear closure and a release, as /t/ and /d/ in coda position can have various phonetic realizations depending on the segment following them (e.g., [ɾ] in *ea**t** it*, [ʔ] in *ea**t** that*). Despite this variability, children seem to assume that /t/ and /d/ in *eat* and *hide* words are produced as [t] and [d]. Song et al., (2015) examined the children's production of coda /t/ and /d/ in the Providence Corpus (Demuth et al., 2006), the data used in the present study. It was found that the 2-year-olds produced the non-canonical variants of the stop codas, i.e., [t̚], [d̚] , [ɾ] and [ʔ], less frequently than adults. This finding provides indirect evidence that [t] and [d] can be considered the phonetic realization /t/ and /d/ in *eat* and *hide* words, at least in children's speech.

4.1.4 Attested learning trajectory

I divided the children's learning process into three stages, i.e., early, intermediate and later stage, focusing mainly on the change of frequency of [t], [d] and [ɾ] in suffixed words.

(2) Attested learning trajectory

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[3] It could have been the case that the children tried to produce flaps (in order to imitate how their caregivers speak) but ended up producing [d] due to articulatory constraints.

	Early stage (~750 days)	Intermediate stage (750~850 days)	Later stage (850~1450 days)
/eating/	[t] attested **[d]** > [ɾ]	[t] not attested **[d]** > [ɾ]	[t] not attested [d] < **[ɾ]**
/hiding/	**[d]** > [ɾ]	**[d]** > [ɾ]	**[d]** > [ɾ]

The change of relative frequency among variants was rather dramatic for *eating* words. In the early stage, roughly before age of 750 days, [t] variants were attested, though the frequency was not very high. Also, the frequency of [d] was higher than that of [ɾ]. In the intermediate stage, between 750 and 850 days, [t] was no longer attested, and [d] was still more frequently observed than [ɾ]. In the later stage, from the age of 850 to 1450 days, the pattern was reversed, as the words were more frequently realized with [ɾ] than with [d].
It seems that the pattern of realization of /d/ in *hiding* words is quite stable across all stages. Some variability is found, however, when we examine the data in more detail. The frequencies of each variant in the four types of words, i.e., *eating*, *potty*, *hiding* and *ready* words, are presented in (3).

(3) Attested variants and their frequencies in each stage

	Early	**Intermediate**	**Later**
eating			
t	37	0	1
d	56	24	27
flap	22	21	101
deleted	16	21	59
glottal stop	6	1	15

potty			
t	0	0	0
d	28	36	30
flap	1	8	30
deleted	7	11	29
glottal stop	0	1	0
hiding			
t	0	0	0
d	27	7	33
flap	4	2	21
deleted	7	0	17
glottal stop	2	0	1
ready			
t	0	0	0
d	16	6	25
flap	0	2	81
deleted	10	2	41
glottal stop	2	0	0

It should be noted that the dominance of [d] over [ɾ] persists for a longer period of time in *hiding* words than for *ready* words. By the later stage, while the frequency of [d] is much lower than that of [ɾ] for *ready* words, [d] variants observed for *hiding* words still outnumber [ɾ] variants. Thus, it can be inferred that OO-faithfulness constraints are active in children's grammar.

In addition, it is worth noting that the ratio of [d] to [ɾ] in *hiding* words decreases over time; although [d] occurs more frequently than [ɾ] in all stages, its dominance becomes weaker. I further divided the later stage into three sub-stages and found that in the second sub-stage, the frequency of [d] and [ɾ] were the same, and in the third sub-stage, the frequency of [ɾ] was higher than that of [d] (though the frequencies were too low to be reliable):

(4) Change in the relative frequency of [d] and [ɾ] within the later stage

	850~950	950~1150	1150~1450 (days)
[d]	20	12	1
[ɾ]	7	12	2

Unfortunately, since the corpus contained no speech data collected when children were older, the learning stage was not observed in which they were able to pronounce flaps actively. But the direction of change in the relative frequency of [d] and [ɾ] might reflect that OO-faithfulness constraints were being demoted to give rise to more [ɾ] variants.

The observed learning trajectory reported in this section was modeled by means of learning simulation, the result of which is presented in Section 6.

4.2 Adults' production of intervocalic /t/ and /d/

4.2.1 Realization of intervocalic /t/ in adult speech

As mentioned earlier, mothers' production of intervocalic /t/ and /d/ were investigated with two objectives. The first was to explore potential influence of input on children's production of the target words; the observed pattern of production in child speech might simply be a reflection of how mothers speak to children, rather than motivated by initial biases. The other was to construct the adult grammar, the target grammar that the children are supposed to learn. In this way, we can supplement the learning trajectory by comparing children's grammar with adults' grammar.

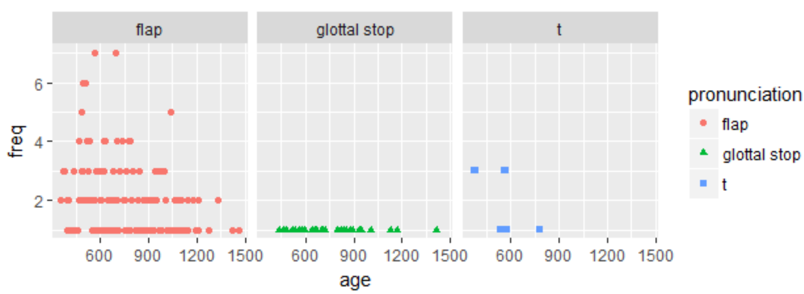
Figure 8 shows attested variants of /t/ in *eating* and *potty* words in adult speech. As expected, both types of words were predominantly produced with flaps. Crucially, [t] variants were also attested in mothers' speech, though the frequency was not high. In *eating* words, 9 tokens were realized with [t] accounting for 3% of the total number of tokens, and only one token was realized as such in *potty* words, accounting for 1% of the total. Although the number of tokens is not large enough, it seems that mothers do produce [t] in *eating* words more frequently than in *potty* words. Assuming that mothers' production of [t] in *eating* words cannot be due to undominated OO-faithfulness constraints, I conjecture that mothers produce [t] in *eating* words in order to inform the child of the fact that base forms (e.g., *eat*) and their suffixed counterparts (e.g., *eating*) are morphologically and semantically related.

Figure 8. Attested variants of intervocalic /t/ in *eating* and *potty* words in adult speech. The numbers indicate the percentage of tokens coded as each variant out of all tokens analyzed.

	ɾ	ʔ	t	Ø	d	others	excluded
eating	82	8	3	2	1	1	3
potty	92	1	1	1	1	2	4

Now that we have seen that mothers also produce [t] for *eating* words, we should ask whether children's production of [t] is to satisfy high-ranked OO-faithfulness constraints, or to mimic the way mothers speak. The fact that both mothers and children produce [t] only at the initial stages of learning (i.e., before the age of approximately 750 days; see Figure 9) seem to support the latter possibility. Specifically, it might have been the case that mothers produce [t] for *eating* words only when the children were less experienced in learning, and during the same period children also produced [t] in order to mimic the frequencies of each variant in mothers' speech. Note, however, that the probability of producing [t] was higher in the children's speech (8%) than in the mothers' speech (3%). Also, if the frequencies in children's speech were to match the frequencies in the input, the probability of producing [ʔ] should be higher; children produced [ʔ] only 4% of the time, while mothers did so for 8% of the time. This conclusion should be taken with care, though, as it is based only on a small number of tokens. In order to test whether frequencies of each variant in children's speech match those of input, a larger set of data will be necessary.

Figure 9. Distribution of [ɾ], [ʔ] and [t] in *eating* words in mother's speech across children's age (in days)



4.2.2 Realization of intervocalic /d/ in adult speech

Mothers' production of /d/ in *hiding* and *ready* words were also analyzed. Figure 10 shows that mothers realized /d/ predominantly as flaps in both *hiding* and *ready* words, as expected. As was the case in *eating* words, mothers also produced [d] for *hiding* words. The fact that they produced [d] much less for *ready* words suggests that their production of [d] in *hiding* words served to provide the children with phonological cues to morphological relationship between two words, e.g., *hide* and *hiding*.
Comparing children's production of /d/ in *hiding* and *ready* words Figure 5 with that of mothers', we find that the attested frequencies of each variant do not match in two registers. While mothers produced [ɾ] most frequently in both *hiding* and *ready* words, the probability of producing [ɾ] in children's speech differed significantly between the two contexts.

Therefore, it does not seem to be the case that children's probability of producing each variant is determined by the relative frequencies observed in the input.

Figure 10. Attested variants of intervocalic /d/ in *hiding* and *ready* words in adult speech. The numbers indicate the percentage of tokens coded as each variant out of all tokens analyzed.

	ɾ	d	Ø	ʔ	others	excluded
hiding	83	7	3	3	1	3
ready	90	2	4	0	2	2

5. Analysis

In this section, OT constraints are introduced that can explain the production of both children and mothers. I will only consider candidates that can be considered typical variants of /t/ and /d/, i.e., [t], [d], [ɾ], [ʔ], and [Ø] (deletion), which account for a significant portion of the surface realizations of the stops in either children or mothers' speech.

5.1 Flapping

First, a constraint is needed that triggers flapping. It is well known in the literature that flap is distinguished from the alveolar stops [t] and [d] by its extra-short closure duration (Banner-Inouye, 1995; Steriade, 1999; Zue & Laferriere, 1979). I assume that the durational difference between flap and the stops can explain why [t] and [d] are banned but a flap is allowed in certain phonological contexts. The constraint in (5) bans intervocalic [t] and [d] (when followed by an unstressed vowel.)

(5) *VTV̌
No intervocalic alveolar stops.

Considering that flaps only appear in restricted environments in English, we need a context-free markedness constraints that bans flaps.

(6) *ɾ
No flaps.

When underlying /t/ or /d/ surfaces as a flap, several IDENT constraints are violated. As noted in Bernhardt & Stemberger (1998), the relevant constraints are ID-IO(son) and ID-IO(voi). When /t/ surfaces as a flap, both constraints will be violated (assuming that flaps are [+son], [+voice]); when /d/ surfaces as a flap, only ID-IO(son) will be violated.

(7) ID-IO(son)
The value of the feature [sonorant] of an input segment must be preserved in its output correspondent.

(8) ID-IO(voi)
The value of the feature [voice] of an input segment must be preserved in its output correspondent.

In addition to these two IDENT constraints for [voice] and [sonorant], I also introduce an IDENT constraint for the feature [extra-short closure]. According to Steriade (2000), it is not satisfactory to use [sonorant] in distinguishing flap from [t] and [d], when we have to capture the connection between occurrence of a flap and the shortening context that triggers it. As I mentioned earlier, I assumed that the motivation for the constraint in (5) is the durational difference between flap and the stops. Therefore, it is appropriate to establish IDENT constraints for the durational feature, although it is phonologically non-contrastive.

(9) ID-IO(dur)
The value of the feature [extra-short closure] of an input segment must be preserved in its output correspondent.

The constraints introduced so far can explain the general phonology in American English, the flapping process in particular.

5.2 Occurrence of [d]

The results in Section 4 showed that children seemed to produce [d] as an alternative pronunciation to flaps, partially because producing flaps is challenging from an articulatory point of view. I assume that [d] is selected as an output since it is similar to [ɾ] than any other consonant is. Crucially, for the present purpose, we need a constraint that can rule out [t] but favor [d], as children were found to produce [d] even when the underlying segment was /t/. The main difference between [t] and [d] that makes only [d] a legitimate output is the specification for the feature [voice], as Bernhardt and Stemberger (1998) also pointed out that when the child stopped producing si[t]ing and began to produce si[d]ing, the [+voice] portion of flap was acquired. Therefore, a constraint that militates against intervocalic voiceless alveolar stop must be established.

(10) *V[-voice]V
No intervocalic voiceless alveolar stop.

The candidate with [t] variant will be penalized by both constraints (5) and (10), and is expected to show a lower probability of being selected as an output than [d].

5.3 OO-faithfulness constraints

OO-faithfulness constraints must be established in order to explain the children's tendency to base their pronunciation of derived words (e.g., *eating*) on the corresponding base forms (e.g., *eat*). Analogous to the constraints in (7), (8) and (9), three OO-faithfulness constraints will be introduced, each targeting [sonorant], [voice] and [extra-short closure].

(11) ID-OO(son)
The value of the feature [sonorant] of an output segment must be preserved in its output correspondent.

(12) ID-OO(voi)
The value of the feature [voice] of an output segment must be preserved in its output correspondent.

(13) ID-IO(dur)
The value of the feature [extra-short closure] of an output segment must be preserved in its output correspondent.

5.4 [ʔ] and deletion

It was observed that children occasionally produced [ʔ]. It seems that in order to avoid producing [ɾ] (or because they cannot produce it), children chose some other variants such as [ʔ]. When an underlying /t/ or /d/ surfaces as a [ʔ], the place features are deleted. The IDENT constraint is needed that militates against the deletion of place features.

(14) MAX-IO(place)
The place node of an input segment must have a

corresponding place node in the output. (No deletion of place features.)

Since glottal stops only appear in restricted environments in English, we need a context-free markedness constraint that bans [ʔ].

(15) *ʔ
No glottal stops.

We also have to account for the fact that children often deleted the consonant, as in *ea*[Ø]*ing*, though not much attention has been paid to deletion throughout the discussion so far. When underlying /t/ and /d/ are deleted, it violates MAX constraint:

(16) Max-IO (C)
Consonants in the input must have output correspondents.

The constraints established so far are needed in explaining the children's production of /t/ and /d/, and were used in learning simulation to model the children's learning trajectories.

6. Learning simulation

Based on the constraints adopted in the previous section, a learning simulation was conducted using Maxent Grammar Tool (Hayes, 2009). In Maximum Entropy model (Goldwater and Johnson, 2003), constraint weights are determined in a way that maximizes the probability of the observed frequency of output forms. Three independent learning simulations were conducted, each of them modeling the children's grammar in the early, intermediate, and later stage in the learning trajectory (see (2)). I aimed to show that change in the ranking among constraints can explain different production patterns of children at each stage. Crucially, the main interest was whether the demotion of OO-faithfulness constraints can in fact predict the observed frequencies of each variant. Learning data were established based on production data of the children (see Appendix 1). The learner was run in a default setting (mu=0, sigma^2 =100,000). The table in (17) presents the constraint weights learned.

(17) Constraint weights learned (shading = OO-faith)

Early	
*V[-voice]V	1.574843
Max(C)	1.567362
*glottal stop	1.441587
ID-IO(place)	1.441587
ID-OO(voi)	0.705321
*flap	0.516116
ID-IO(dur)	0.516116
ID-IO(son)	0.516116
*VTV	2.12E-22
ID-OO(dur)	0
ID-OO(son)	0
ID-IO(voi)	0

Intermediate	
*V[-voice]V	13.48348
*glottal stop	2.303081
ID-IO(place)	2.303081
Max(C)	1.810609
ID-IO(voi)	0.827867
ID-OO(voi)	0.581723

*flap	0.264649
ID-IO(dur)	0.264649
ID-IO(son)	0.264649
ID-OO(dur)	0
ID-OO(son)	0
*VDV	0

Later	
*V[-voice]V	4.891813
*glottal stop	1.412748
ID-IO(place)	1.412748
Max(C)	0.755463
*VTV	0.706174
ID-IO(voi)	0.450731
ID-OO(voi)	0.053268
*flap	2.22E-05
ID-IO(dur)	2.22E-05
ID-IO(son)	2.22E-05
ID-OO(dur)	0
ID-OO(son)	0

The OO-faithfulness constraints were expected to be ranked high initially and demoted gradually in the learning process. Unfortunately, such change in constraint ranking was not observed. One unexpected outcome was that ID-OO(dur) and ID-OO(son) were assigned a zero weight even in the early stage. By examining the production data, however, we can understand why they were assigned zero weight. Note that the role of these two constraints is to enhance the ratio of [d] to [ɾ] in *eating* and *hiding* words, compared to *potty* and *ready* words, respectively. In other words, as [ɾ] violates ID-OO(dur) and ID-OO(son) while [d] does not, the two constraints will increase the probability of producing [d], but only in the suffixed words. This was not the actual story, however. As

noted in 4.1.1., the probability of producing [d] in *eating* words was lower than in *potty* words (which was true for all periods). The two OO-faithfulness constraints are thus assigned zero weight.
Because it was actually the case that the ratio of [d] to [ɾ] in *hiding* words were much higher than *ready* words, at least in the later stage, ID-OO(dur) and ID-OO(son) might have had an effect. The fact that ID-OO(dur) and ID-OO(son) only targets *hiding* words but not *eating* words is hard to understand. The results of the learning simulation might have been better if I had assumed distinct OO-faithfulness constraints for /t/ and /d/ words, but this idea is counter-intuitive.

7. Conclusion

The present study aimed to provide empirical evidence for the claim in McCarthy (1998) and Hayes (2004) that OO-faithfulness constraints are undominated at the initial stage of learning, but are gradually demoted in the learning process as the learners encounter violations of those constraints in the input. With the case of American English flapping, the production data of six English learning children provided evidence that they indeed showed bias for non-alternation, enforced by high-ranked OO-faithfulness constraints, and that such bias became weaker over time. There are remaining problems, however. First, we should more carefully examine the influence of input on children’s speech production to test the claim in McCarthy (1998) and Hayes (2004) more adequately. Also, in order to successfully model the learning trajectories with learning simulation, it is necessary to have a better understanding of the reasons why children produce in a certain way and therefore to construct a proper set of OT constraints.

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