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## 1. Introduction<sup>1</sup>

A great deal of recent research has addressed the representation of laryngeal features (Avery 1996; Avery & Idsardi 2001; Iverson & Salmons 1995, 2003; Jessen 1989, 1996; Jessen & Ringen 2002; Lombardi 1991, 1995, 1999, 2001; Salmons & Iverson, to appear; Steriade 1995, 1997; Van Rooy & Wissing 2001; Vaux 1998; Wetzels & Mascaró 2001). Debates in the literature focus on several major aspects of phonological theory, including monovalent versus bivalent features, gradient versus categorical processes, and phonetic detail in phonological representation. In discussions of these issues, evidence from a range of sources has been used, including phonetics, phonology, typology, and diachrony. Surprisingly, very little evidence from acquisition has been brought to bear on the issue of laryngeal representation.

Acquiring the laryngeal phonology of a language amounts to identifying the relevant contrasts, building up a representation of laryngeal features, and learning to produce these contrasts in an adult-like fashion. By studying children's developing language systems, we can gain insight into how laryngeal features are represented. Acquisition patterns provide a way to test claims about the representations of laryngeal features. This paper presents corpus analyses of the acquisition of initial obstruents in Dutch and German, and the acquisition of initial and final obstruents in English. Children's productions of voiced and voiceless obstruents were analysed for realizations of laryngeal features. These analyses revealed a number of interesting error patterns.

First, productions of children acquiring Dutch, which is a so-called prevoicing language, differ from productions of children acquiring German and English, which are aspiration languages. Production errors of children learning Dutch tend to favor voiceless stops in initial position, whereas children learning German (Grijzenhout & Joppen-Hellwig 2002) and English (Menn 1971; Smith 1973) exhibit the opposite error pattern, producing more voiced stops. This confirms earlier results from acquisition studies of prevoicing languages such as Spanish and Hindi (Macken & Barton 1980b; Davis 1995) and of aspiration languages such as English and German (Macken & Barton 1980a).

Second, the frequency of voicing in children's targets that children attempt to produce does not reflect the error patterns related to voicing. For example, while production errors of young children acquiring Dutch show a trend toward initial voiceless stops (/b/ → [p] and /d/ → [t]), a statistical analysis of children's targets reveals rather the reverse trend: children

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attempt more voiced than voiceless word-initial stops. This finding implies that children's error patterns reflect factors other than frequency of targets in children's productions, such as articulatory factors or featural representation.

Lastly, children's voicing errors in English turn out to be conditioned by the laryngeal specification of segments occurring later in the word; more specifically, the devoicing of initial stops is triggered by a following voiceless obstruent. However, no 'harmonic' effect is found for the voicing of initial obstruents when followed by voiced obstruents.

These acquisition data were used to test different theories' claims of how laryngeal features should be represented in languages that display a two-way laryngeal contrast: either with a single binary feature [ $\pm$ voice] (Wetzels & Mascaró 2001), or multiple language-dependent features, specifically monovalent [voice] and [spread glottis] (Iverson & Salmons 1995).<sup>2</sup> Results from this study will be argued to support Iverson & Salmons' theory, in which aspiration languages (including English and German) use the feature [spread glottis], while prevoicing languages (including Dutch) use [voice].

Importantly, our study supports a multiple feature view, under which languages use one constant active feature to represent their laryngeal contrasts in all positions, initial and final. The harmony pattern observed in English acquisition data supports this view: interaction between initial and final obstruents implies a shared monovalent featural representation for voicing in these positions, which abstracts from specific phonetic realization. A purely phonetic account cannot readily account for this pattern.

This paper is organized as follows. Section 2 will discuss the major theories of laryngeal representation to be considered, stating predictions they make for error patterns in children's productions in English, Dutch and German. In Section 3, we will discuss Dutch acquisition data, which we will compare with German data in Section 4. Then we will find that children acquiring Dutch, a prevoicing language, produce errors involving devoicing of stops that are voiced in the target word, whereas the available German data show rather the reverse pattern, in which consonants that are voiceless in target words are produced as 'voiced' or more accurately, as plain unaspirated stops. In comparing the acquisition data from Dutch, a prevoicing language, and German, an aspiration language, two major interpretations will be considered: a phonetic one, based on intrinsic properties of children's early production and perception systems, and a phonological one, based on the Multiple Feature Hypothesis. In section 5, these hypotheses will be tested on English, using a corpus-based study of the early productions of a single child, whose laryngeal error patterns will be discussed in detail. We will argue that error patterns involve the activity of [spread glottis] in a laryngeal harmony pattern affecting only voiceless consonants in coda and onset of a word. This will be interpreted as evidence for a representation of laryngeal contrasts involving multiple features, [voice] (for prevoicing languages) and [spread glottis] (for aspiration languages). Finally, we will discuss consequences of our findings in Section 6.

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<sup>2</sup> An alternative to Iverson & Salmons' multiple laryngeal features is that of Avery and Idsardi (2001) who express the features in more phonetic terms in three dimensions: Glottal Width (for aspiration languages like English), Glottal Tension (for voicing languages, such as Dutch) and Larynx Height for languages which have ejectives or implosives in their segment inventories. In this paper, we use the terminology [voice] and [spread glottis] to express the phonological contrasts.

## 2. Theories of laryngeal representation

### 2.1 One versus multiple features

The phonetic realization of laryngeal contrasts<sup>3</sup> varies across languages. The main acoustic cue associated with voicing is voice onset time or VOT, which refers to the time between a segment's release and the beginning of vocal cord vibration. There are a number of ways in which laryngeal contrasts are realized in languages (Cho & Ladefoged 1999). In the languages studied in this paper, a two-way contrast is employed. However, there are also languages that employ a six-way contrast, as for example Beja (Cushitic) and Igbo (Kwa) (Ladefoged, 1973, cited in Iverson & Salmons, 1995: 382). For the purpose of this paper, however, it is important to note the VOT differences in stops<sup>4</sup> across Dutch, German and English. These values (based on Lisker & Abramson, 1964; Braunschweiler, 1997) are given in Table 1.

=== PLACE TABLE 1 HERE ===

The laryngeal contrasts in these three languages can be divided into those that exhibit voicing lead (where voicing begins before the release), short lag VOT (where voicing begins at the time of the release or shortly afterwards), and long lag VOT (where there is a delay between the release and the beginning of voicing). In languages such as Dutch, the contrast in initial position is one between voicing lead and short lag VOT, while in aspiration languages such as German, the initial contrast is one between short lag and long lag VOT (where long lag VOT results in voiceless aspirated stops). Similar to Dutch are languages such as French and Spanish. Similar to German are English and most other Germanic languages (except Dutch and Germanic languages such as Afrikaans, Frisian, and Yiddish).

The question then naturally arises as to whether the featural representations of prevoicing and aspiration languages are different. There are two primary views in the literature. The standard approach within current phonological theories assumes that a single feature captures the laryngeal contrasts of all languages with a binary contrast, generalizing across prevoicing languages and aspiration languages. This single feature is either a binary feature [ $\pm$ voice] (Steriade 1995; Wetzels & Mascaró 2001), or monovalent [voice] (Mester & Itô 1989; Cho 1990; Lombardi 1995, 1996). For the purposes of this paper, we refer to these theoretical variants as the Single Feature Hypothesis. Laryngeal specifications for Dutch, German and English for both variants are given in Tables 2 and 3.

=== PLACE TABLE 2 HERE ===

=== PLACE TABLE 3 HERE ===

Note that the laryngeal contrasts of Dutch, German and English are captured with the same distinction between [+voice] and [-voice] (or [+voice] and [    ]), but the acoustic correlates for these features differ for Dutch versus German and English.

A second approach to laryngeal features was advanced by Jessen (1989, 1996) and Iverson & Salmons (1995, 2003), who argue that laryngeal features are best represented with

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<sup>3</sup> Here we focus on word-initial stops.

<sup>4</sup> VOT interacts with place of articulation features (Lisker & Abramson 1964): dorsal stops have a longer VOT than both coronal and labial stops; in turn, coronal stops have a longer VOT than labial stops.

multiple monovalent features such as [voice] and [spread glottis]. In languages with a binary laryngeal contrast, only one of these (the active feature) is underlyingly specified. A language's selection of laryngeal feature can be diagnosed by its active phonological processes, and it tends to correlate with VOT properties of stops. This approach will be referred to as the Multiple Feature Hypothesis since it assumes two monovalent features, [voice] and [spread glottis].<sup>5</sup> According to Iverson & Salmons, prevoicing languages, such as Dutch, represent the laryngeal contrast by a monovalent feature [voice], such that voiced stops are specified and voiceless stops are unspecified. Aspiration languages, such as German and English, select the active feature [spread glottis], such that aspirated stops (voiceless) are specified, and unaspirated stops (voiced or voiceless) lack specification, indicated by [ ]. The laryngeal specifications under this approach for Dutch, German and English are given in Table 4.

=== PLACE TABLE 4 HERE ===

Under the Multiple Feature Hypothesis, the Dutch voicing contrast is expressed by representing pre-voiced stops with the feature [voice], while voiceless segments lack specification in their phonological representation. Aspiration languages such as German and English represent their laryngeal contrast with [spread glottis] on aspirated stops, and lack of specification on plain (unaspirated voiceless) stops. Note that both [voice] and [spread glottis] are abstract phonological features in the sense that their phonetic realizations vary and depend on the position in the word. For example, [spread glottis] is realized with maximal aspiration (i.e. fully abducted vocal folds) only in the onset of foot-initial syllables, while other positions have weaker implementations (Iverson & Salmons 1995:377).

Having sketched the Single Feature Hypothesis and the Multiple Feature Hypothesis, we are now in a position to turn to acquisition, which provides a testing ground for theories of laryngeal feature representation.

## 2.2 Acquisition of laryngeal contrasts: Previous studies

Previous studies on the acquisition of voicing have found developmental differences between prevoicing and aspiration languages. With respect to the time course of acquisition, it appears that laryngeal contrasts are acquired later in prevoicing languages than in aspiration languages (Macken & Barton 1980ab, Davis 1995). While the Dutch contrast is acquired some time around the age of three (Kuipers 1993ab, Beers 1995), the English contrast is acquired relatively early, by the age of two (Macken & Barton 1980a). Previous research (Davis 1995) has indicated a role of acoustic salience in these acquisition differences, where prevoicing (voicing lead) is argued to be less salient than aspiration (long lag VOT). This suggests that some of the acquisition differences seen in languages are to some extent attributable to ease of perception and, possibly, production. However, differences in acoustic salience across languages do not exclude the possibility that differences in acquisition are due to different feature representations across languages. This paper will explore the phonetic versus phonological accounts for the patterns seen in acquisition.

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<sup>5</sup> Other monovalent features may also be used to capture laryngeal contrasts cross-linguistically, such as [constricted glottis] or [stiff vocal cords]. Languages may have more than one feature; for example, Thai, which has a three-way laryngeal contrast, employs both features [voice] and [spread glottis].

### 2.3 Further assumptions and predictions

The accuracy of children's productions can be taken to reflect children's phonological knowledge and representations. Children's production errors have been argued to reflect innate universal grammar (Jakobson 1941/1968 and others), given that children's production errors can often be characterized as neutralizing to the unmarked value. For example, children often delete final consonants and produce CV syllables, e.g., *taart* /ta:rt/ 'cake' is produced as [ta...] in Dutch (Fikkert 1994), *Tag* /tag/ 'day' as [dʒa...] in German (Kerstin 1;5, see below), and *tape* /teyp/ as [tʰe...] in English (Seth 1;7, see below). These production errors can be interpreted as reflecting phonological knowledge, such as the knowledge that the universally preferred syllable shape is a CV syllable. It is a well-known observation (Jakobson 1941/1968) that criteria for markedness based on cross-linguistic evidence are supported by language acquisition, as children tend to produce the least marked properties before more marked ones (cf. Zamuner 2003; Zamuner, Gerken & Hammond 2005). Returning to the example of syllable structure, we note that children initially produce the least marked CV syllables, before producing more marked syllable shapes, such as those with final consonants (Fikkert 1994, Levelt et al. 2000).

Assuming Jakobson's hypothesis that children's initial errors reflect the unmarked values of phonological features, we can derive a number of predictions regarding children's error patterns, based on the Single Feature Hypothesis and the Multiple Feature Hypothesis. These predictions are given in Table 5.

=== PLACE TABLE 5 HERE ===

Recall that the Single Feature Hypothesis makes use of a single binary feature of [ $\pm$ voice] or monovalent feature [voice]. The unmarked value for this theory is invariant across languages, because all languages utilize the same feature to represent laryngeal contrasts. With a binary feature, this unmarked value is [-voice]. If children's initial productions tend toward the unmarked value, this would predict that the direction of errors is cross-linguistically uniform, and should be independent of the language that children are acquiring. Accordingly, children learning Dutch, German or English are all predicted to make devoicing errors [+voice]  $\rightarrow$  [-voice]. These errors would affect words starting with (marked) [+voice] consonants, while words starting with (unmarked) [-voice] consonants should not be affected. (For a monovalent feature, predictions are essentially the same, although the specifications are slightly different.) In contrast, the Multiple Feature Hypothesis would predict differences between prevoicing and aspiration languages regarding the types of consonants that are affected. Languages with prevoicing should display devoicing errors [voice]  $\rightarrow$  [ ] (omission of the feature [voice]) in words starting with (marked) voiced consonants, while words starting with (unmarked) [ ] voiceless consonants should not be affected, whereas children acquiring aspiration languages should produce deaspiration errors [spread glottis]  $\rightarrow$  [ ] (omission of the feature [spread glottis]) in words starting with (marked) aspirated consonants, while words starting with (unmarked) unaspirated consonants should not be affected. In Table 6, the predictions are spelled out in terms of phonetic symbols.

=== PLACE TABLE 6 HERE ===

In sum, using Jakobson's hypothesis that children's errors are changes in the direction of the unmarked, theories of laryngeal representation make different predictions about consonants

which are prone to undergo errors in acquisition. Hence, the acquisition of Dutch versus German and English provides an excellent test case for these theories.

### 3. Dutch

To test the predictions of the Single and Multiple Feature hypotheses, we collected acquisition data from Dutch, German, and English. Different corpora from the CHILDES database were studied. We will start with a discussion of the Dutch data, which were taken from the CLPF database (Fikkert 1994, Levelt 1994). The data from 11 Dutch monolingual children whose ages range between 1;0 and 2;11 were studied; this involved approximately 20,000 utterances. Examples of voicing errors are below.

(1) Examples of laryngeal errors in Robin's utterances

a.	douche	'shower'	tus	(1;10.21)
b.	dier	'animal'	ti@	(1;10.21)
c.	beer	'bear'	pi	(1;7.13)
d.	bal	'ball'	pAl	(1;7.13)
e.	baby	'baby'	pipi	(1;8.10)
f.	thuis	'home'	d{ys	(1;5.10)

(2) Examples of laryngeal errors in Tom's utterances

a.	boot	'boat'	pO	(1;5.0)
b.	bal	'ball'	pA	(1;5.14)
c.	bed	'bed'	pEt	(1;5.28)
d.	doen	'do'	tun	(2;1.14)
e.	paard	'horse'	bat	(1;3.24)

Only productions of initial stops /b/, /p/, /d/ and /t/ were considered. These stops had to be faithfully realized for place of articulation to be included in our analyses. Dutch lacks the voicing contrast in velars; hence we did not consider the velar stop /k/. Also, fricatives were not included, because in many Dutch regions the distinction between voiced and voiceless fricatives is disappearing (Slis & van Heugten 1989; Ernestus 2000; Van de Velde et al. 1996; Van de Velde & van Hout 2001).

Not all children were monitored for the same period of time: Figure 1 shows the ages of the different children in the database. Note that at the beginning and end of the age span, data were collected for only one or two children: Tom at 1;0, Leon at 2;9 and Noortje at 3;0.

=== PLACE FIGURE 1 HERE ===

In Figure 2, the number of target words is given for each child. Note that the number of tokens is given here: for types, a similar pattern was found. In the remainder of the discussion of Dutch, we will only present results from token analyses. Figure 2 shows that all children attempted more voiced targets (/b/ and /d/-initial words, a total of 4871 targets) than voiceless targets (/p/ and /t/-initial words, a total of 2244 targets). On the basis of this, one might predict that children will be more accurate when producing voiced targets than when producing voiceless targets, but we will see that we find the opposite pattern: overall, children produced more voiceless than voiced stops.

=== PLACE FIGURE 2 HERE ===

Figure 3 shows the error percentages of all children when producing word-initial stops. These percentages were determined by averaging the percentage error rate across children.

=== PLACE FIGURE 3 HERE ===

In Figure 3, all errors children made in the voicing value of word initial segments are shown. Thus it collapses errors made both in voiced and voiceless segments. Children's productions become more faithful during the time they were studied. Apparently, the overall development curve is U-shaped, but this appearance is caused by the fact that at the age periods 1;0, 2;9 and 3;0 there are only data from one or two children. Noortje, who is the single child providing data at 3;0, was found to be late in her overall phonological development (Fikkert 1994). Hence, she causes a rise of the curve at this point. Her error rate for the production of initial stops remains quite high during the entire period in which she was studied.

When errors are broken down by place of articulation, we see that this factor does not play any crucial role in the production of the voice value. In Figure 4, the errors are broken down for labial-initial words (/b/ and /p/) versus alveolar-initial words (/d/ and /t/). There is no significant difference (*t-test*,  $p=0.11$ , two-tailed) between the error rates of these two places of articulation, hence, we find no evidence that voicing in labials is either more or less difficult than voicing in alveolars.

=== PLACE FIGURE 4 HERE ===

=== PLACE FIGURE 5 HERE ===

In Figure 5, error rates are split for voicing errors (e.g., /p/ and /t/ produced as /b/ and /d/) and devoicing errors (e.g., /b/ and /d/ produced as /p/ and /t/). This clearly shows that there were more devoicing errors ( $M=42.75$ ,  $SD=22.6$ ) than voicing errors ( $M=9.25$ ,  $SD=11.01$ ). This difference is significant (*t-test*,  $p\leq 0.01$ , two-tailed), and holds for every stage. For all children, we see that devoicing errors persist well into the third year, while the rate of voicing errors drops to almost 0%.

We can also examine the extent to which Dutch children's initial 'voicing' production patterns reflect the distribution of voicing in the input (Van der Feest 2004, to appear). For this analysis, we analyzed child-directed speech from the van de Weijer corpus (van de Weijer 1998). This corpus contains speech directed to a child between the ages of 2;6 and 2;9 (a selection of 18 days appears in the corpus). We conducted (type and token) counts of initial voiced and voiceless stops for different places of articulation. Results are summarized in Table 7.

=== PLACE TABLE 7 HERE ===

There is a preference for voiced stops in both type and token counts in child-directed speech. This means that the error patterns seen in Dutch production data (voiceless stops are produced before voiced stops) cannot be accounted for by input frequencies.<sup>6</sup>

To summarize these data, we can say that overall, Dutch children acquire the voicing system quite late, having not yet completed it by the age of 2;6. We have seen that for the acquisition of the Dutch voicing contrast, there is no significant effect of place of articulation. Also, although more target words have voiced onsets, children make more errors in voiced than in voiceless initial segments, while their overall productions contain more voiceless than voiced segments. These findings support the featural specification [voice] for Dutch, assuming that unmarked voiceless segments are acquired before the marked voiced segments.

However, the acquisition data from Dutch are consistent with both the Single Feature Hypothesis and the Multiple Feature Hypothesis. Under the latter hypothesis, voiceless segments are assumed to be unspecified for the monovalent feature [voice], and hence, predicted to be acquired before specified voiced segments, while under the former hypothesis (assuming a single binary feature [ $\pm$ voice]), voiceless segments would also be predicted to be acquired first. Here, voiceless segments are specified as [-voice], and would be less marked than voiced segments, which are specified as [+voice]. Since predictions from these hypotheses are identical, Dutch acquisition data could, in principle, never produce any crucial evidence deciding between these hypotheses. It is important, though, that the acquisition patterns cannot be explained on the basis of input frequency.

Still, the two approaches predict different orders of acquisition for the German segments. The Multiple Feature Hypothesis, which assumes that aspiration languages such as German represent the laryngeal contrast by [spread glottis], would predict that voiced segments are acquired first, since these are unspecified for [spread glottis], and hence unmarked. The Single Feature Hypothesis, on the other hand, assumes voiceless segments to be universally specified as [-voice], and for that reason would predict such (unmarked) segments to be acquired first. We now turn to a discussion of German to see which of the two approaches is supported by our acquisition data.

#### 4. German

German is an aspiration language, which differs from prevoicing languages such as Dutch in encoding its two-way laryngeal contrast by aspiration versus non-aspiration, at least in word onset position. As pointed out above, the Multiple Feature Hypothesis represents the German laryngeal contrast as one of [spread glottis] for aspirated /p/, versus [ ] for plain /b/ (Jessen 1996, Jessen & Ringen 2002). Accordingly, the prediction from this hypothesis is that the production errors of children acquiring German will be predominantly of the /p<sup>h</sup>/ → [b<sup>9</sup>] (or 'lenition') type, matching a neutralization of the feature [spread glottis]. Phonetically, such errors would amount to a failure to realize aspiration on a stop that is lexically specified as [spread glottis].

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<sup>6</sup> One could also look at the frequency of voiceless vs. voiced stops collapsed across different prosodic positions, i.e. collapsed across word-initial, word-medial and word-final position (see Zamuner, 2004). Based on these types of calculations, one finds that voiceless stops are overall more frequent than voiced stops. Input frequencies would then match the patterns of production seen in Dutch acquisition data.

German data were collected from the Nijmegen Database in CHILDES (MacWhinney 1999).<sup>7</sup> We considered data from the only child in the database for which sufficient phonetic transcription was available, Kerstin (aged 1;3 - 3;4). From this large longitudinal database (containing approximately 25,000 utterances) we selected Kerstin's productions between ages 1;0 and 2;2, which allowed us to track her development with respect to laryngeal specifications.

Some characteristic examples of Kerstin's deaspiration errors are given below:

- (3) Examples of 'voicing' errors in Kerstin's utterances
- |    |       |         |  |
|----|-------|---------|--|
| a. | Papa  | 'daddy' | baba (1;5.7, 1;6.20, 1;7.24, 1;10.3, 1;11.20, 2;0.5) |
| b. | Puppe | 'doll'  | bibbaa (1;3.22), bubbaa (1;3.22)                     |
| c. | Tag   | 'day'   | daa (1;5.3)  |
| d. | Teddy | 'Teddy' | diddie (1;5.6), dide (1;6.13), didi (1;7.24, 1;8.22) |
| e. | Turm  | 'tower' | dum (2;3.1)  |

Note that the informal transcription indicated in the corpus of items such as *Papa* as 'baba' and *Tag* as 'daa' suggests pre-voicing, rather than just deaspiration. This was presumably due to a language-specific bias on the part of the transcribers, who may have perceived unaspirated stops as lenis stops /b, d/. We will interpret the transcriptions conservatively as evidence for deaspiration only. In comparison, only a very small number of errors in the opposite direction was found. The single clear example is *Becher* (1;5.17) transcribed in the corpus as 'peschel', presumably phonetically [p<sup>h</sup>œsʃ]. The near complete absence of initial devoicing/aspiration in Kerstin's utterances contrasts with the situation in English, as we will see in Section 6.

Quantitative analysis confirms that Kerstin's errors are almost exclusively of the 'voicing' type: an unaspirated realization of stops corresponding to aspirated stops in the adult language. See Figure 6.

=== PLACE FIGURE 6 HERE ===

Errors of the 'devoicing' type were extremely rare, while 'voicing' errors are abundant. This matches earlier observations for German acquisition (Grijzenhout & Joppen-Hellwig 2002). The prediction of the Multiple Feature Hypothesis is thus borne out.

To what extent does Kerstin's initial 'voicing' pattern reflect the statistics of the input? We carried out an analysis of child-directed speech in the same CHILDES corpus, based on utterances from caretakers present during recording sessions in the relevant periods (Kerstin's age 1;0 - 1;12). We conducted (type and token) counts of initial voiced and voiceless stops for different places of articulation. Results are summarized in Table 8.

=== PLACE TABLE 8 HERE ===

There is a noticeable trend toward voiced initial stops (especially for labials) in child-directed speech during Kerstin's second year.<sup>8</sup> Kerstin's error pattern is thus compatible with the input

<sup>7</sup> Data in the Nijmegen database were collected and transcribed by Susan Powers, Juergen Weissenborn, Wolfgang Klein, Heike Behrens, and Max Miller

<sup>8</sup> The stronger trend toward voicing in tokens can be attributed to the fact that many prefixed words start with /b/ or /g/. A related issue, which we leave for future work, is how prosodic factors (mainly, stress) affect the

she received. But although Kerstin's input matches the direction of her errors, input statistics alone cannot account for the error pattern. This is because Kerstin produced virtually no errors of the devoicing type during her second year, a much stronger result than might be expected on the basis of the input pattern alone.

In sum, the error pattern of a German child between ages 1;0 and 2;3, showing abundant voicing errors in initial stops, but hardly any devoicing errors, is naturally accounted for by the Multiple Feature Hypothesis as omission of the active feature [spread glottis], but not by the Single Feature Hypothesis, while an input-based account offers only a partial explanation.

## 5. Interpretation and further predictions

Summarizing so far, we found that the acquisition of the initial voicing contrast in Dutch is rather slow, and completed beyond the age of 2;6. Errors are predominantly of the 'devoicing' type. For German, the initial contrast is acquired earlier, and seems completed by the age of 2;0. Errors are overwhelmingly of the 'voicing' type (presumably, lenition or deaspiration).

Two plausible interpretations of these findings suggest themselves, one phonological and the other phonetic. A strongly phonological account, which we have been assuming thus far, seeks a featural basis for the observed developmental differences. On the assumption that errors in early productions target the unmarked feature value, findings for Dutch and German would favor the Multiple Feature Hypothesis over the Single Feature Hypothesis, since only the former predicts differences in error patterns between the languages. The Multiple Feature Hypothesis models the Dutch voicing contrast on a monovalent feature [voice], and hence would correctly predict production errors of Dutch children to result in featurally unspecified stops, which are phonetically interpreted as 'voiceless'. The German laryngeal contrast, as opposed to Dutch, is based on a monovalent feature [spread glottis], which predicts German children's production errors to favor unspecified stops, phonetically realized as 'unaspirated' (that is, lenis and voiceless). The Single Feature Hypothesis, on the other hand, represents both languages by a single feature [voice], and hence would not predict any differences in the directionality of laryngeal errors between German and Dutch developmental patterns, as both languages would represent their contrasts by a single feature. (Note that, as indicated in Table 6, differences may occur between phonetic errors patterns in voicing and aspiration languages due to the language-particular implementation of the specifications [voice] and [ ].)

However, an alternative articulatory interpretation might be proposed, which would explain differences in error patterns between the languages, and hence would leave no room for testing the two representational hypotheses discussed above. According to what we will refer to as the 'Articulatory Effort Hypothesis', young children's initial preference for short lag VOT (that is, unaspirated voiceless stops) is due to lack of articulatory skills necessary to produce stops with either long lag VOT (aspiration) or short lead VOT (prevoicing). This would correctly predict that early German productions show a lack of aspiration, while early Dutch productions show a lack of prevoicing. To account for the developmental differences between German and Dutch (i.e., age of acquisition of the contrast), the additional assumption would be needed that prevoicing is more difficult to produce than aspiration (Kewley-Port & Preston 1974, van Alphen this volume). Alternatively, a perceptual account may be given

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salience of laryngeal contrasts in the input. For example, contrasts in onsets of stressed syllables may be more salient than those in unstressed syllables, such as prefixes.

following Davis (1995) and others: on the basis of greater perceptual salience of long lag VOT as compared to short lead VOT, children acquire the laryngeal contrast in aspiration languages earlier than in prevoicing languages.

The Articulatory Effort Hypothesis explains properties of children's errors in relation to the target language, but its validity need not rule out a role of featural representations in the explanation of error patterns. We are thus facing the following question: when considering children's laryngeal errors, how to distinguish effects of articulatory effort from effects of feature specifications? Here is an attempt to tease the two kinds of effects apart.

The Articulatory Effort Hypothesis would predict that errors correlate with the overall motoric complexity of a target. As is well-known, the articulatory effort required for the realization of a gesture may also depend on its position in an utterance. For example, it is much easier to maintain voicing in intervocalic contexts than in word-initial or final contexts. However, motoric effort should be independent of the presence of a target elsewhere in the utterance, specifically when they are not adjacent (for example, when two consonants are separated by a vowel), or when the targets are articulatorily diverse. Cross-linguistically, the articulatory gestures for laryngeal contrasts and the acoustic cues are quite varied. Cues include VOT, closure duration, duration of the preceding vowel (Keating 1984). Within a language, choice of laryngeal gesture may depend on a segment's position in the word, in the syllable, or on neighbouring segments. For example, English realizes laryngeal contrasts in onset mainly by VOT, and laryngeal contrasts in coda mainly by duration of the preceding vowel, closure duration, or glottalization. In sum, the Articulatory Effort Hypothesis would predict few interactions in error patterns between articulatorily heterogeneous positions, such as the onset and coda in English.

In contrast, a phonological account would predict contrastive specifications to appear in children's error patterns, which abstracts from fine-grained phonetic realization depending on position. For example, a phonological account would predict cases of 'laryngeal harmony' between onset and coda, in which only contrastive features would harmonize, not redundant ones.<sup>9</sup> (Cross-linguistic studies on laryngeal cooccurrence patterns include MacEachern 1997, Hanson 2001, Rose & Walker 2001.) It should be emphasized that by 'harmony' we generally refer to any kind of interaction between segments which produces identical contrastive feature specifications, without implying autosegmental spreading resulting in doubly-linked features. As Fikkert & Levelt (2002) argue, consonant harmony at early stages of development may be driven by a general requirement for stops to be featurally similar, regardless of whether similarity is achieved by spreading, by default, or by phonologically active features.

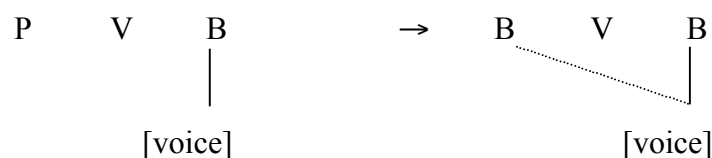
Radical underspecification of contrastive features would make an additional prediction that production errors reflect activity of the specified feature only, to the exclusion of the unspecified value. Under the Multiple Feature Hypothesis, laryngeal features are monovalent, mainly to capture the observation that voiceless unaspirates are unmarked both in prevoicing and in aspiration languages. Languages differ as to which feature is specified: [voice] in prevoicing languages such as Dutch, and [spread glottis] in aspiration languages such as English. Underspecification thus creates predictions about harmony, since only unspecified segments should be the targets, assimilating non-locally to specified segments.

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<sup>9</sup> As far as we know, no gestural accounts have been proposed which assign a single laryngeal gesture to onset and coda, thus spanning an entire syllable. Such accounts would necessarily be more abstract than the standard accounts, moving closer to a phonological representation.



(6) Harmony predicted by the Multiple Feature Hypothesis: prevoicing languages



Note that the Multiple Feature Hypothesis and the monovalent version of the Single Feature Hypothesis make similar predictions for prevoicing languages. Predictions differ between the ‘monovalent’ frameworks, however, for aspiration languages. If the Multiple Feature Hypothesis is correct, English uses monovalent [spread glottis], and hence should display anticipatory harmony of the ‘devoicing’ type /BVP/ → [PVP], whereas if the Single Feature Hypothesis is correct, anticipatory harmony should be of the ‘voicing’ type, /PVB/ → [BVB].

In sum, to compare predictions made by the Single Feature Hypothesis and Multiple Feature Hypothesis, we must distinguish monovalent and binary variants of the latter. If children’s productions were to contain systematic patterns of voicing harmony, but not devoicing harmony, this pattern would be compatible with both the Multiple Feature Hypothesis and the monovalent version of the Single Feature Hypothesis, but it would form evidence against its binary version. Next, if harmony of the voicing and devoicing type were to systematically co-occur in a child’s productions, this would support the binary version of the Single Feature Hypothesis, but form evidence against both monovalent accounts. Finally, if we were to find that children’s production errors consistently display devoicing harmony, while lacking voicing harmony, this asymmetrical pattern would favor the Multiple Feature Hypothesis, but constitute evidence against the monovalent and binary variants of the Single Feature Hypothesis. The logical options are summarized in Table 9:

=== PLACE TABLE 9 HERE ===

Let us now turn to a test case for the Multiple Feature Hypothesis against the Single Feature Hypothesis: English.

## 6. English

English acquisition data may serve as a test case, since this language precisely meets the conditions under which harmonic anticipations of laryngeal features might occur. First, English matches German (but not Dutch) in being an aspiration language. Hence, under the Multiple Feature Hypothesis [spread glottis] is specified, predicting this feature to be active in children’s early phonologies. Indeed, English-learning children display deaspiration errors (Menn 1971). Second, unlike German, English lacks syllable-final laryngeal neutralization, so that coda obstruents are specified contrastively. Since onsets and codas both license laryngeal specification, harmony effects become potentially visible. This meets the logical requirement which must be fulfilled for testing for positional interactions involving [spread glottis].<sup>10</sup>

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<sup>10</sup> Dutch and German have word-final neutralization, hence monosyllables cannot be used to test predictions on laryngeal harmony. Logically, laryngeal harmony might affect initial and medial consonants in polysyllables in these languages, but unfortunately, relevant cases in the Dutch and German databases were too rare to base any conclusions on.

## 6.1 Earlier studies

Earlier studies (such as Smith 1973) provide evidence for initial voicing and final devoicing in children's productions. Let us first turn to some data from Smith (1973). During the first half of his third year (ages 2;2 - 2;6), Amahl realized most of his initial stops as plain (voiceless unaspirated), by a general neutralization of initial laryngeal contrasts. In this period, initial neutralization affects voiced targets (for example, *bell*), as well as voiceless ones (for example, *pen*). (We adopt Smith's transcription.)

(7) Initial stops realized as voiceless unaspirated, irrespective of targets (ages 2;2 - 2;6)

- a. bell [b<sup>h</sup>E] (2;2)
- b. pen [b<sup>h</sup>En] (2;2)

In the same period, Amahl also neutralized most word-final stops to voiceless. Since this has audible consequences only for voiced targets (e.g. [mOb<sup>h</sup>] for *knob*), the overall effect is one of final devoicing.

(8) Final stops realized as voiceless (unaspirated), irrespective of targets (ages 2;2 - 2;5)

- a. knob [mOb<sup>h</sup>] (2;2)
- b. stop [d<sup>h</sup>Op](2;2)

Amahl's development during this period is shown in Figure 7. The error percentages were calculated as the proportion of target words of which the laryngeal realization, [p], [b<sup>h</sup>], or [b], deviated from the target specification, /p/ or /b/.<sup>11</sup> For target / b/, for example, any realizations deviating from it, either [p] or [b<sup>h</sup>], were considered as devoicing errors.

=== PLACE FIGURE 7 HERE ===

Note that the final contrast is acquired slightly earlier than the initial contrast, by about a month. The error rate of final devoicing drops sharply round age 2;5, while that of initial neutralization (as shown in the two topmost lines) follows at the distance of about a month.

The observation that Amahl's laryngeal contrast stabilizes slightly earlier in final than in initial position may come as a surprise, given that the child is unlikely to receive input with the laryngeal distinction directly realized on the final stop, whereas initial stops have robust VOT cues.<sup>12</sup> However, other cases are known of children acquiring English who mastered the laryngeal distinction in codas before it emerged in onsets (Clark & Bowerman 1986:55, fn. 5; Vihman & Ferguson 1984:383; Fey & Gandour 1982; but see Stoel-Gammon & Buder 1999). More generally, other consonant types, such as fricatives and liquids, are more likely to be first acquired in final position (Ferguson 1978, Stoel-Gammon 1985).

At best, we can offer speculative accounts of the coda-onset lag in Amahl's laryngeal development, as no acoustic data are available for verification. One account would attribute the lag to production factors rather than lexical representation; Amahl may have mastered control over vowel duration, the primary realization of laryngeal contrast in coda, before the

<sup>11</sup> Analysis is necessarily based on types, since Smith (1973) does not present token counts.

<sup>12</sup> Amahl's mother spoke English as her fourth language, after Hindi, Bengali and Marathi. According to Smith (1973:7-8), her speech was characterized by 'fuller voicing of voiced obstruents'.

gestural coordination between release and voice onset which is required for aspiration. Under this scenario, lexical representations in onset and coda are stable at an earlier stage, setting the stage for rapid across-the-board changes once the relevant gestures are mastered. Indeed, Amahl shows a rapid development of the laryngeal contrast in onset and coda, both of which are completed within approximately three months. Nevertheless, an explanation of the coda-onset lag based on developing lexical representations cannot be ruled out, because laryngeal error rates vary somewhat between individual lexical items, an observation which is difficult to explain under a production-only account. For example, during period 10-11 (at the age of 2;6) all three occurrences of *bread* had neutralized onsets, while all three occurrences of *Braj* (a name) were realized correctly. Hence, it is quite possible that Amahl's laryngeal contrast was lexically represented in final position before it emerged in initial position.

Relative strength of the laryngeal contrast in coda position will become a major factor in our central case study, to which we turn next.

## 6.2 Seth: a case study

The data in this section were taken from a large CHILDES database (Wilson & Peters 1988), containing approximately 12,500 utterances, with a total number of 39,000 words. All data were from a single monolingual child, named Seth, aged between 1;7 - 4;1, who was acquiring American English. Utterances in the database are matched with target words in plain orthography, and are phonetically transcribed at a level allowing for qualitative and quantitative analysis of voicing patterns. The original sound files were kindly made available to us in digitized form by Ann Peters and Brian MacWhinney for further transcription and acoustic analysis.

We monitored Seth's development between ages 1;7 and 2;5, the period during which major changes in the laryngeal contrast took place, and at the end of which Seth's productions of the contrast were largely indistinguishable from adults.

### 6.2.1 Initial devoicing

We first focused on word-initial position and collected all of Seth's productions of content word<sup>13</sup> targets containing an initial voiced or voiceless stop. This allowed us to search for factors which possibly influenced the proportion of two major types of error: initial 'voicings' (actually, deaspirations resulting in plain stops) and initial 'devoicings' (actually, aspirations). The resulting dataset contained 227 types and 4354 tokens. Table 10 shows type and token distributions of initial voiced and voiceless target stops, for different places of articulation.

=== PLACE TABLE 10 HERE ===

A representative set of examples of initial errors in Seth's early utterances are given below:

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<sup>13</sup> Stop-initial function words rarely occurred during the early stages of Seth's development. Moreover, targets for function words were difficult to establish.

(9) Initial devoicing in Seth's utterances

Labials			
a.	bark	[paak]	1;8
b.	boy	[pay]	1;9
c.	bike	[payk]	1;10
d.	backpack	[p'kp'k]	1;11
Alveolars			
e.	Dabee	[tabiy]	1;7
f.	doughnut	[townaa]	2;0
g.	dog	[tagiy]	2;2
h.	drink	[trunk]	2;5
Velars			
i.	geese	[kiys]	1;8
j.	go	[ko]	1;8
k.	got it	[kaaDit]	2;2
l.	get	[ket]	2;3

(10) Initial voicing in Seth's utterances

Labials			
a.	penny	[b'niy]	1;11
b.	play	[bwedjø]	1;11
c.	peanut butter	[bi bødø]	1;11
d.	play	[beydl]	2;1
Alveolars			
e.	tape	[deyp]	1;9
f.	trunk	[drøNk]	1;10
g.	tan	[d'n]	2;0
h.	tell	[d'ø]	2;0
Velars			
i.	kiss it	[giset]	1;8
j.	kitchen	[gisøN]	1;9
k.	cookie	[gukiy]	1;10
l.	cool	[guw]	1;10

Although both types of initial errors are abundant, Seth makes more devoicing errors than voicing errors in initial position, as shown in Table 11. This presents token counts of voiced and voiceless targets (/B/ and /P/) and their realization (voiced [B] or voiceless [P]) over a succession of four three-month periods (1;7 - 2;5), where the last column gives the results collapsed across periods. In the notation we use, B refers to voiced (labial, coronal, or velar) stops, and P to voiceless stops. Error percentages are indicated in cells for unfaithful realizations. For example, for the period 1;7 - 1;9, the corpus contains 415 targets with initial voiced stops, 372 of which were realized faithfully, and 43 of which (10.4%) were devoiced.

=== PLACE TABLE 11 HERE ===

Over the monitored period (1;7 - 2;5), both error types decreased continuously. To determine whether devoicing errors were more frequent than voicing errors, a series of chi-square tests was conducted. Results were significant for all periods except the period of 2;3 – 2;5.

Figure 8 shows the direction of initial errors in tokens (devoicing versus voicing) as it develops between the ages of 1;7 and 2;5.

=== PLACE FIGURE 8 HERE ===

Note that devoicing errors occur about twice as frequently as voicing errors throughout Seth's development.

The dominance of devoicing errors extends to types, as Table 12 shows:<sup>14</sup>

=== PLACE TABLE 12 HERE ===

The high proportion of devoicing errors in the early productions of an English learning child apparently clashes with our previous observations for German, where 'voicing' (actually deaspirating, lenition) errors prevailed. It seems to run against the typological prediction made in Section 2, according to which aspiration languages would display errors of the 'voicing' (deaspiration) type, so that English would parallel German. Upon closer inspection, however, we see that Seth's initial devoicings are not simply neutralizations to the unmarked value.

When we differentiate Seth's initial devoicing errors according to their contexts in the word, it becomes clear that following consonants play a major conditioning role. Figure 9 shows that initial devoicing is much more frequent in targets in which a voiceless obstruent follows (e.g., *bark*, *drink*, *geese*) than in targets which have no following voiceless obstruent (e.g., *boy*, *dog*, *go*):

=== PLACE FIGURE 9 HERE ===

We used a chi-square test to test the difference in error rates between target categories (words with a following voiced obstruent, a following voiceless obstruent, or no following obstruent), over the entire period (1;7 – 2;5), and found a strong effect ( $\chi^2 = 45.4$ ,  $p \leq 0.001$ ).

Next, to establish whether voiced obstruents differed from sonorants in their effects on initial devoicing, we broke down the category 'no voiceless consonant following'. Table 13 shows devoicing in three target types: (a) /B...P/ targets, which have a following voiceless obstruent (e.g. *back*, *diaper*, *grass*), (b) /B...B/ targets, which have a voiced obstruent (e.g. *baby*, *dog*, *give*), and (c) /B...R/ targets, which have a following sonorant or vowel ('R') (e.g. *ball*, *door*, *gone*). For each period, Seth's productions are broken down into faithful [B...] and unfaithful [P...] realizations of the target, and error rates are indicated in 'unfaithful' cells.

=== PLACE TABLE 13 HERE ===

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<sup>14</sup> If a single type occurred as both voiced and voiceless, it was coded as unfaithful. For example, *bark* was coded as [P...] because it occurred with both voiced and voiceless initial stops.

Throughout Seth's development, initial devoicing rate is highest for /B...P/ targets. Over the four periods, this error type reaches a much higher average (of 8.7 %) than targets /B...B/ and /B...R/ (both 2.4 %). Note that in all three categories, a gradual overall reduction of devoicing errors occurs.

The difference between /B...P/ targets and the other targets /B...B/ and /B...R/ turned out to be statistically significant, as Table 14 shows. This compares initial devoicing rates for three targets (/B...P/, /B...B/, /B...R/) for all four periods. Chi-square tests were conducted for the token distribution in Table 12, establishing that /B...P/ targets undergo devoicing significantly more often than targets /B...B/ and /B...R/, while any differences in devoicing rate between /B...B/ and /B...R/ targets are non-significant.

=== PLACE TABLE 14 HERE ===

In sum, devoicing in /B...P/ targets is significantly more frequent than for other targets across periods. It is more frequent than devoicing for /B...B/ targets in two out of four periods, and more frequent than devoicing for /B...R/ targets in three out of four periods. Also, /B...B/ and /B...R/ targets cannot be distinguished in terms of the initial devoicing rate.

We interpret these results as follows. In targets that begin with a voiced obstruent, a following 'P' (voiceless) segment triggers initial devoicing, as compared to a following 'B' (voiced) or 'R' (sonorant) segment, which behave as inactive with respect to initial devoicing. Initial devoicing in /B...P/ targets results in outputs with identical laryngeal features between the word onset (which undergoes it) and a following [spread glottis] obstruent (which triggers it). This is arguably a case of laryngeal harmony of the type that was predicted in Section 5 (Table 9). Consequently, this finding supports predictions of the Multiple Feature Hypothesis: English, a language using [spread glottis] to represent its laryngeal contrast, should display activity of this feature in laryngeal harmony, if such harmony were to be found.

Note also that segment types predicted to be phonologically inactive by the Multiple Feature Hypothesis, 'B' (voiced obstruents) or 'R' (sonorants), are indeed inactive. Devoicing rates for target words with following 'B' or 'R' segments fall well below the rate observed for /B...P/ targets. Their shared behavior is predicted by lack of specification for [spread glottis] under the Multiple Feature Hypothesis. Note that no other featural theory under consideration predicts a shared behavior, since voiced obstruents will be marked [voice], while sonorants will not bear a distinctive laryngeal representation.

How to account for the fact that initial devoicing marginally occurs in the other targets /B...B/ and /B...R/? We attribute the initial devoicing rate for these targets, which amounts to 2.4% on average in the period 1;7 – 2;5, to the instability of early lexical representations. That is, the early lexicon contains incomplete featural information for lexical items, manifesting itself in variable productions, with both voiced and voiceless realizations. We suggest that during early production, lexically incomplete featural information is supplemented by three sources. First, context-free markedness effects (that is, omission of [spread glottis]) amount to context-free neutralization, which we observed as voicing in /P.../ targets. Second, copying of the active feature [spread glottis] amounts to laryngeal harmony in /B...P/ targets. Thirdly, a certain amount of random selection occurs. Initial devoicing in targets /B...B/ and /B...R/ occurs when random selection fills in incomplete features in early lexical representations. The fact that initial devoicing is facilitated by, but not categorically restricted to, /B...P/ targets, can thus be explained by an interplay of harmony effects and random specification.

To verify the amount of initial ‘devoicing’ (actually, aspiration) in Seth’s productions, we now turn to the results of phonetic analysis.

### 6.2.2 Phonetic analysis

In order to determine whether devoicing results in a full merger with target voiceless stops, we carried out narrow phonetic transcriptions and conducted acoustic measurements of VOT. First, all stop-initial items (between ages 1;7 and 1;9) were extracted from the digitized sound material. Next, 79 items were removed due to bad quality. For the remaining 605 items, narrow phonetic transcriptions were made by five transcribers (the current authors), and an acoustic analysis (VOT measurements) was conducted.

Figure 10 shows mean VOT values (in msec) for Seth’s voiced and voiceless stops (ages 1;7 - 1;8). Seth’s values closely approximate the adult VOT values.

=== PLACE FIGURE 10 HERE ===

The following criteria were applied for determining an item’s error status. A ‘devoicing error’ was defined as an item whose target has a voiced onset and which was realized with VOT > 30 msec (for labials and alveolars), or with VOT > 50 msec (for velars), and which was also categorized as ‘voiceless’ by a native listener (one of the current authors). A ‘voicing error’ was defined as an item whose target has a voiceless onset and which was realized with VOT < 30 msec (for labials and alveolars), or with VOT < 50 msec (for velars), and which was also categorized as ‘voiced’ by the native listener.

Analysis showed that Seth’s devoicing errors resulted in initial stops (e.g. *geese*, *bark*) with mean VOT values which approximate mean VOT values for target voiceless stops (e.g. *tape*). See Figure 11.

=== PLACE FIGURE 11 HERE ===

On the basis of these findings, we feel safe in assuming that devoicing errors are ‘categorical’, in the sense that devoiced target consonants are acoustically indistinguishable from faithfully realized voiceless consonants.

### 6.2.3 Initial voicing

We now turn to target words whose initial consonants are voiceless, and look into patterns of initial voicing, in order to find out whether voiced obstruents behave as phonologically inactive, as predicted by the Multiple Feature Hypothesis.

First, we are interested in the question whether Seth’s productions show any effects of anticipatory voicing harmony, analogously to initial devoicing.

=== PLACE FIGURE 12 HERE ===

Surprisingly, hardly any voicing harmony occurs. The initial voicing rate for /P...B/ targets falls significantly below that of other targets /P...P/ and /P...R/ ( $\chi^2 = 11.7$ ,  $p \leq 0.001$ ). That is, the prediction from the Multiple Feature Hypothesis that voiced obstruents are phonologically inactive is confirmed. We momentarily put aside the question of what causes the harmony-avoiding pattern in /P...B/ targets, and break down the data for /P...P/ and /P...R/ targets, respectively.

Data are broken down for following consonants ‘P’, ‘B’ and ‘R’ in Table 15, which is the counterpart of Table 13 (for initial devoicing).

=== PLACE TABLE 15 HERE ===

/P...P/ and /P...B/ targets display a gradual decrease of initial voicing errors during Seth’s development. As noted above, the case of /P...B/ is most interesting since it shows no voicing errors except one in the first period. As compared to /P...B/, target /P...R/ shows more errors.

Differences between categories turn out to be actually much smaller than in the case of initial devoicing, when measured by chi-square tests. Table 16 compares initial voicing rates of targets /P...P/, /P...B/, and /P...R/.

=== PLACE TABLE 16 HERE ===

Phonological inactivity of final /B/ (voiced obstruents) becomes clear from Tables 15 and 16. Since the rate of initial voicing for /P...B/ targets falls far below that of other targets /P...P/ and /P...R/, we may safely conclude that final voiced obstruents fail to condition anticipatory voicing harmony. Non-occurrence of voicing harmony is straightforwardly predicted by the Multiple Feature Hypothesis on the assumption that English is a [spread glottis] language (see again Table 9).

Table 16 also shows significant differences during the first two periods between on the one hand, /P...P/ and /P...B/, and on the other hand, /P...P/ and /P...R/. Since in terms of its featural specification [spread glottis], /P/ forms no natural class with /B/, nor with /R/, both of which are unspecified, these findings are compatible with the Multiple Feature Hypothesis. Note, however, that the relative ease of initial voicing in /P...P/ targets is not predicted by this hypothesis, which has nothing to say about non-harmonic effects. If initial voicing amounts to context-free neutralization, the question is why final /P/ apparently facilitates it. Below we will offer an answer based on the maintenance of lexical contrast. But first we turn to another surprising result shown in Table 16.

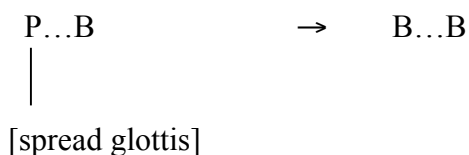
The surprising finding is that /P...B/ and /P...R/, which ought to be indistinguishable by the non-specification of /B/ and /R/, nevertheless significantly differ in period 1;10-1;12, where /P...B/ hardly shows any initial voicing, while /P...R/ does. Upon closer inspection, we find that the inhibitory effect in /P...B/ targets is caused by a single word, *please*, having 170 occurrences in this period, all of which fail to undergo initial voicing. Since *please* is a highly frequent item in Seth’s corpus, the inactivity of its initial consonant may be attributed to its relatively stable lexical representation. The high rate of initial voicing in /P...R/ targets in the middle periods (1;10 - 2;2) is mostly due to alveolar stops: five cases of *turn*, all realized in rapid succession in a single recording session, and two cases of *tan*. Interestingly, the voiced realizations of these items were always preceded by nasals (for example, [søn d’n] ‘sun tan’,

and [n da' af] ‘N turn off’, where the nasal is apparently a realization of ‘want’), suggesting a post-nasal voicing process in Seth’s phonology. Since alveolar stops regularly alternate with flaps in American English, these may also have been early attempts at flapping. In sum, we suggest that initial voicing in /P...R/ targets is due to phonological factors applying across word boundaries, rather than phonological activity of sonorants following within the target.

In sum, there is no evidence for voicing harmony triggered by /P...B/, confirming the predictions of the Multiple Feature Hypothesis. Target /P...R/ shows no initial voicing except for a temporary unexplained increase during a single period. For /P...P/, some development is visible, with high levels of initial voicing during earlier periods, followed by a sharp decline. It thus seems that segment types /P/, /B/ and /R/ cannot be distinguished as to their effect on initial voicing. This finding is predicted by the central hypothesis that ‘voicing’ errors amount to a context-free neutralization, a delinking of [spread glottis] → [ ], not conditioned by segments elsewhere in the word.

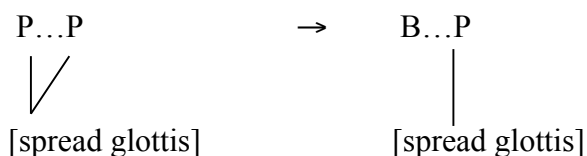
Finally, we turn to the unexplained low proportion of initial voicing errors in /P...B/ targets. As in German, we attribute initial voicing to context-free omission of [spread glottis], reflecting the instability of early lexical representations. Neutralization occurs at an average level of 2.9% in /P...P/ targets, whereas it is strongly inhibited in /P...B/ (average 0.2%). Our speculative account again starts from the hypothesis that initial voicing amounts to delinking of [spread glottis]). We observe that the key difference between the targets /P...P/ and /P...B/ is that the former contains two [spread glottis] elements, and the latter only one. We suggest that blocking of initial delinking in /P...B/ targets reflects an avoidance of wholesale deletion of [spread glottis].

(11) Initial delinking resulting in complete loss of specified [spread glottis]



The avoidance of initial delinking in /P...B/ and /P...R/ may thus be construed as a way of maintaining the laryngeal contrast by preserving the single occurrence of [spread glottis].

(12) Initial delinking resulting in partial loss of specified [spread glottis]



In contrast, /P...P/ targets have two occurrences, so that initial delinking still preserves one.

In sum, the observed asymmetry between onset devoicing and onset voicing in Seth's early word productions gives evidence from acquisition for the activity of [spread glottis] in English. Phonologically active coda obstruents are lexically specified for this feature, while voiced obstruents and sonorants are unspecified, hence phonologically inactive. The Single Feature Hypothesis predicts the observed asymmetry, while other models under consideration fail to account for it.

However, two important questions remain. First, the issue of directionality of harmony effects arises: is laryngeal harmony from coda to onset matched by harmony in the reverse direction, triggered by the onset, and effected in the coda? Second, a major issue arises as to whether the laryngeal harmony as witnessed in /B...P/ targets is due to lexical specification, or rather to surface realization. That is, we assumed that the influence of [spread glottis] is located at the level of lexical representation, but have not presented any evidence bearing on this. We will discuss both issues below.<sup>15</sup>

To answer these questions, we need to look at word onsets and codas separately. For this reason, we will now turn to a selection of Seth's productions, his monosyllables.

#### 6.2.4 Directionality of harmony: Seth's monosyllables

Although the Multiple Feature Hypothesis makes no predictions<sup>16</sup> about the directionality of laryngeal harmony, we are nevertheless interested in directionality effects in Seth's data, for two reasons. First, directional asymmetries in laryngeal harmony might provide clues about early lexical representations, related to the relative strength of specification for onset and coda consonants. Second, directionality in laryngeal harmony would strengthen the similarity with other types of consonantal harmony in language acquisition and in speech production. A well-known asymmetry in directionality is found in consonant harmony in children's productions (Menn 1971, Smith 1973, Pater & Werle 2001, to appear, Fikkert & Levelt 2002) as well as in adult speech errors (Fromkin 1973, Shattuck-Huffnagel 1979, Stemberger 1991a, b) including anticipations of voicelessness. We will first address the issue of whether laryngeal harmony is unidirectional in Seth's productions, affecting onsets only, or bidirectional, affecting codas as well.

Before comparing contextual effects in onset and coda devoicing, we briefly address the relative stability of the laryngeal contrasts in onsets and codas in Seth's monosyllables. Figure 13 shows laryngeal error rates for final and initial stops, respectively, during four stages.

=== PLACE FIGURE 13 HERE ===

During the earliest stage (1;7–1;9), when Seth's anticipatory devoicing pattern was at its peak, error rates for initial obstruents are slightly (although not significantly) above those for final ones. This suggests that the laryngeal contrast in final position is relatively stable as compared to initial position in early stages of phonological development. Speculatively, this would tie in

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<sup>15</sup> A third question, which we will briefly address at the end of this section, concerns item-specificity: to what extent is the devoicing effect restricted to particular target words?

<sup>16</sup> Of course, we predict that if right-to-left (perseverative) laryngeal harmony were to be found, then it should be of the devoicing type, rather than of the voicing type, since English employs [spread glottis] as its active feature. However, coda voicing effects were generally too rare in Seth's productions for this prediction to be testable.

with our earlier finding about Amahl's development (Section 6.2, Figure 7), who acquired a stable laryngeal contrast in coda slightly before it stabilized in onset.

The relative stability of the coda contrast naturally leads to the expectation that onset devoicing may be facilitated by voiceless codas, but not vice versa. This expectation stems from the assumption (see Section 6.2.1) that laryngeal harmony is related to the instability of early lexical representations in the sense that harmony amounts to the influence of a relatively stable lexical specification (typically, a coda) onto a less stable one (typically, an onset). To test the predicted lack of harmony in coda devoicing, we compared onset and coda devoicing in Seth's monosyllables, assessing the degree to which each is contextually conditioned by a voiceless obstruent. From the earlier mentioned database we extracted all targets (151 types, 3064 tokens) starting with a stop, which was voiced in about half of the cases (51.0% of types and 52.8% of tokens). We also extracted all targets (146 types, 2406 tokens) ending in a stop, which was voiced in about one third of the cases (32.9% of types, 28.9% of tokens).

To assess the relative strength of contextual factors in onset and coda devoicing, we first counted voiced and voiceless realizations of /B.../ monosyllables into three categories, whose target ended in a voiceless obstruent, voiced obstruent, or sonorant (including vowels). We will refer to these categories as /B...P/, /B...B/ and /B...R/ respectively. We then counted voiced and voiceless realizations<sup>17</sup> of /...B/ monosyllables, for the three target categories /P...B/, /B...B/, and /R...B/. Characteristic examples of coda devoicing in Seth's database are [bet] 'bed' (1;9) in the category /B...B/, and [fayNt] 'find' (2;2) in the category /P...B/. The results are shown in Table 17 and Table 18.

=== PLACE TABLE 17 AND TABLE 18 HERE ===

Again, a strong effect is found for the contextual conditioning of initial devoicing ( $\chi^2 = 25.15$ ,  $p \leq 0.001$ ). This effect is due to the high proportion of initial devoicing in /B...P/ targets, as compared to other targets. Moreover, as compared to initial devoicing, final devoicing is not contextually conditioned. In spite of some minor differences between targets, there is no effect of onset type ( $\chi^2 = 3.48$ , n.s.), supporting our hypothesis that final devoicing is context-free.

These results point to an interesting asymmetry in the directionality of laryngeal harmony. While onset devoicing anticipates the coda's voicelessness, coda devoicing shows no perseveration of onset voicelessness. That is, laryngeal harmony shares its directionality with other consonantal harmony processes found in acquisition and adult speech errors (see references at the beginning of this section).

Again we argue that the positional interactions in Seth's productions give evidence for an abstract representation of the laryngeal contrast, which is unified between the onset and the coda. As we saw earlier, the phonetic realization for laryngeal contrast in English strongly differ between onsets and codas. In onsets, VOT is the primary cue, while in codas, duration of the preceding vowel, closure duration, and (for some dialects) glottalization, are main cues. Since anticipation of the coda's voicelessness by the onset cannot be reduced to anticipation of the articulatory gestures involved, we have a case that the positional interaction occurs at a more abstract level: that of contrastive specification. This gives evidence from acquisition for representations of laryngeal contrasts involving monovalent features. More precisely, activity

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<sup>17</sup> Other realizations, such as those involving onset deletion, were left out of consideration.

of ‘voiceless’ obstruents (with non-activity of ‘voiced’ obstruents and sonorants) supports the specification of the feature [spread glottis], rather than [ $\pm$ voice].

### 6.2.5 The level of harmony: lexical versus surface specification

The final issue is whether initial devoicing in /B...P/ targets is due to lexical specification, or an effect of surface realization. We already saw some evidence from Seth’s early productions that laryngeal harmony is governed by lexical specification (see Sections 6.2.1 and 6.2.4.). First, the phonological activity of voiceless obstruents, to the exclusion of voiced obstruents and sonorants, demonstrated in Section 6.2, points to a relatively abstract level of representation, which is underspecified for laryngeal features. Second, we discovered two further properties of harmony, its directionality (anticipatory nature) and its non-local nature (passing across an intervening vowel), which both point to lexical representation as the relevant level. Both properties are reminiscent of processes which are assumed to be sensitive to lexical representation, such as speech errors involving place of articulation and voice (see Stemberger 1991a, b).

To further test our hypothesis that lexical specification, not surface realization, is the relevant level conditioning harmony, we checked whether /B...B/ target monosyllables whose final obstruent was produced voiceless due to final devoicing had an increased chance of undergoing onset devoicing as compared to /B...B/ targets whose final consonant remained voiced. As expected, we found no such effect. Thus, for predicting the likelihood for initial devoicing in a /B...B/ item, surface specification of the final obstruent was about equally as informative as its lexical representation. Tentatively, lexical specification alone (not surface realization) may account for laryngeal harmony.

Interestingly, we also found that likelihood of onset devoicing increased as a function of unfaithfulness in the coda, regardless of whether this involved deletion, devoicing, or other segmental changes. This ‘unfaithfulness effect’ was found for /B...B/ targets ( $\chi^2 = 13.61$ ,  $p \leq 0.001$ ), as well as /B...P/ targets ( $\chi^2 = 6.11$ ,  $p \leq 0.025$ ). It need not have a phonological interpretation; instead we suggest a role for general factors affecting accuracy of realization of the word or utterance as a whole.<sup>18</sup>

The tentative conclusion that lexical representations are involved in initial devoicing is supported by evidence from Seth’s monosyllables that shows that onset devoicing is, to some extent, sensitive to lexical frequency of individual items.<sup>19</sup> To test for a correlation between item frequency and onset devoicing, we placed all forty /B...P/ and /B...B/ targets in a rank-order by frequency in Seth’s corpus, split the list into two halves (of most frequent and least frequent items), and calculated the error rates for each list. We found that initial devoicing occurs less often in the most frequent items: only 5.1% of the most frequent items underwent initial devoicing, versus 10.7% of the least frequent items. The frequency effect ( $\chi^2 = 4.01$ ,  $p \leq 0.05$ ) is, of course, compatible with developing lexical representations.

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<sup>18</sup> Some /B...P/ items were found in which initial devoicing occurred even though the final obstruent was left deleted, for example, [pli] ‘blink’ and [kiy] ‘geese’ [1;7]. Although such cases may seem to constitute strong evidence for the relevance of lexical representation, their relevance is somewhat undermined by the observation that deletion in /B...B/ items also increased chances of devoicing in onset. Both cases can be explained by the general unfaithfulness factor discussed above.

<sup>19</sup> Thanks to Joe Stemberger for suggesting this to us.

## 7. Conclusions

This study of the acquisition of laryngeal contrast in three Germanic languages with binary laryngeal contrasts (Dutch, German, and English) offers evidence supporting the language-specific selection of laryngeal features [voice] and [spread glottis]. The Multiple Feature Hypothesis correctly predicts differences between Dutch and German in children's error patterns in initial obstruents, as the result of neutralization to the unmarked value depends on the language-specific laryngeal feature: loss of [voice] for Dutch, and loss of [spread glottis] for German. However, we observed that the Articulatory Effort Hypothesis could also explain the asymmetry between Dutch and German, assuming that prevoicing and aspiration both pose articulatory challenges to the young child, which are avoided by devoicing (in Dutch) and deaspiration (in German), respectively. For Dutch and German, we argued that the error patterns in acquisition cannot be fully explained on the basis of input frequency.

Focussing on evidence from the acquisition of English, we argued that an account based on the phonological feature [spread glottis] explains the observed asymmetry between voiceless obstruents and other consonants. In Seth's early productions, we found anticipatory devoicing, a case of laryngeal harmony, triggered by following voiceless obstruents but not by following voiced obstruents, nor by sonorants. This finding was interpreted as to support the Multiple Feature Hypothesis, i.e. languages with binary laryngeal contrasts differ in their 'active' laryngeal features, either [voice] or [spread glottis]. For English, a language which selects [spread glottis] as its active laryngeal feature, this correctly predicts that only voiceless obstruents trigger harmony.

Finally, we argued that articulatory effort alone cannot account for observed effects of anticipatory devoicing because of its non-local nature and the abstractness of the specification involved. Anticipatory devoicing arguably involves an abstract level of featural organization, that of contrastive specification. We presented additional evidence to support the hypothesis that the level of representation that is relevant for laryngeal harmony is lexical representation: its non-locality, its sensitivity to lexical frequency, and its insensitivity to the presence of the triggering segment in the output.

Perhaps the main interest of harmony patterns in children's productions resides in the possibility of testing the nature of lexical representations in early childhood. Even within a single language, laryngeal contrasts may be realized by rather different articulatory gestures (which correspond to different acoustic parameters) in syllable onset and coda. Evidence from children's early productions for laryngeal harmony between coda and onset, two positions which differ in the articulatory implementations of the laryngeal specification, suggests that young children (starting round the age 1;6) already construct phonological representations that abstract away from the phonetic detail which differentiates specific positions.

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