5. Modelling Language Change

The following sections § 5.1 and 5.2 present two models of language change, based on the concept of language as a deterministic dynamic system, governed by self-organisation. The reductionistic approach states that knowing the characteristics of the constituting elements and their interactions is essential in order to understand the system’s controlling mechanisms. Knowing the mechanisms of a system, enables predictions to be made on the course of the developments taking place in the system. Based on the linguistic characteristics of Frisian in 1300, predictions could be made on the course of the developments. The retrospective approach to historical linguistics offers the opportunity to check the validity of these predictions. The data in this research from the language of the 14th-century Unia codex to early Modern Frisian of the 16th-century charters, covers a sufficient time frame to meet the challenges posed by such modelling.

These models help answering questions, such as:

• Was the order and direction of the transitions in any way predictable, logical or perhaps even inevitable? Or could the development have equally taken another direction or order?
• How did speakers manage to achieve their semantical objectives in a changing language environment?

Section 5.1 demonstrates a causal correlation between the quantitative phonetic features of unstressed vowels and the reduction of unstressed vowels. This reduction process is considered as a type of ‘sound erosion’.

In § 5.2, linguistic signs are evaluated for their quantitative semantical ambiguity in a bidirectional model. In this bidirectional approach, speakers consider both tradition and semantic ambiguity, while acoustic erosion remains a constant force when choosing any realisation. This section demonstrates that:

• Semantic contrasts are maintained while their phonetic realisation changes in a gradual process,
• ‘Mistakes’ or ‘ambiguous parallel forms’ are intrinsic parts of the transition process and their level of appearance can even be predicted. The ‘exceptions’ form part of the ‘rule’.144

144 Tony Feitsma once stated (oral communication by Willem Visser) that “marginal existence is a special case of non-existence, abundant presence is a special case of omnipresence”. A preferable alternative would be: “non-existence is a special case of marginal existence, omnipresence is a special case of abundant presence.”
5.1 Modelling the reduction of /a/ and /ø/ as a phonetic process

The first model shows how it is possible to predict the order and speed of the reduction of unstressed vowels in late mediaeval Frisian from the phonetic features of these sounds in 1300. Vowel reduction is regarded as an erosion process. The vowel realisation is defined in physical, measurable terms, the Intensity Integral Volume (§ 5.1.1). The Intensity Integral Volume, the acoustic ‘mass’ of vowels, depends on their duration, quality and actual position in the word. The impact of the different features is quantified using values from contemporaneous phonetic observations (§ 5.1.2). A combination of Intensity Integral Volume and vowel erosion results in a prediction of order and velocity of vowel reduction (§ 5.1.3). This prediction is checked with real data from the historical sources from chapter 2 (§ 5.1.4). Section 5.1.5 shows how the phonetic parameters can be computed from the historical data, a kind of reverse engineering. Additional aspects of this model are discussed in § 5.1.6.

5.1.1 Vowel ‘mass’: reduction and erosion

The process of vowel reduction in Frisian over the studied time frame runs from /a/ to ø, with /ø/ as an intermediate state. The simplified conclusion is that, where there was ‘something’ at the beginning, ‘nothing’ was left at the end. The question is: what is this something or ‘nothing’ and how can it be expressed?

The model presented in this section is purely phonetic. Phonetic data is measured on continuous scales. Phonology is the categorical organisation of phonetic data. From a reductionistic point of view, phonology emerges from phonetics. It would be ‘greedy reductionism’ to deny any categorical ordering of sounds, as was recently done by Port & Leary (2005). This section takes the categorical interpretation of the phonemes /ø/ and /a/ for granted, but, for the description of their features and the way these might influence their ‘behaviour’ the analysis does not rely on discrete phonological features, but on the underlying phonetic data.145

The mass or volume of a sound is defined both by its duration and its intensity /loudness. The combination of these two features creates an intensity integral, shown in graph 5.1:

145 The categorical interpretation of /a/ and /ø/ does not entirely match the structuralistic definition of a phoneme. The criterion is not that two sounds show minimal pairs, but that they represent two clusters of realisations with different centroids, irrespective of the reason for their separation. Two sounds in one language variant showing an allophonic distribution can show two separated clusters of realisations. In a diatopic case, it is possible to find two clearly different realisations for one ‘underlying’ phoneme. In both examples, structuralistic phonology does not distinguish between different phonemes, but for the purpose of this analysis they are identified as two different categorical groups.
The Intensity Integral Volume is a result of duration and intensity. A sound can have a greater Intensity Integral Volume due to a longer duration but also as a result of increased intensity. On its way from full sound to ø (= ‘nothing’; [ø] is a phonetic notation), the volume of the Intensity Integral is reduced towards zero.

5.1.2 The controlling factors
The previous chapters note that the process of vowel reduction was controlled by the following phonological variables:

1. Vowel quality: /a/ and /œ/ behave differently;
2. Word-finality: Protected vowels show a different development than word-final vowels (babba th ~ babba), and, at a more detailed level, vowels in the word-interior behave differently from protected vowels in the last syllable, cf. abbate ~ babba th, dorena ~ swere n;
3. Word structure: Unstressed vowels that follow a long syllable behave differently to those that follow a short root.

In order to ensure the reliability of an experiment, variables other than the ones that are the subject of the test, should be kept as constant as possible. The reduction of /œ/ to ø (syncope) was sometimes prohibited or delayed by wellformedness constraints. To keep the testing environment constant, the sub-patterning is left out and examples where wellformedness constraints do not pose any obstacle for the developments are concentrated on. Further research with considerably more fine tuning can build this into an extended model.
Section 1.3.3 mentions that the characteristics of the bio-physiological substratum of language (the shape of the speech organs, the working of the brain, the physical laws that describe acoustics, etc.) are universal and do not change during the period 1000 to 2000 AD. This means that existing phonetic measurements can be used on 14th and 15th century language.

As the following sections show, various existing measurements render different results. Each individual has his or her own phonetic characteristics, with sub-variations for speech. To avoid undesirable deviations, examples are taken from modern Germanic languages including Modern West Frisian, Dutch, Scots and Norwegian. Absolute figures found in modern languages are not the main focus. It is the relative numbers which are important, for example: “What is the relative impact of the contrast between word-final and protected position on vowel length?”, rather than: “How long is a protected unstressed vowel?”. Daily practice shows that people are able to deal with different absolute vowel lengths (of different speakers and/or different speech velocities), while still able to distinguish words based on, for example, vowel length opposition. This implies that it is the relative dimensions, not the absolute figures, that matter (cf. Rietveld & Van Heuven 1997, 223). The following procedure builds on these assumptions.

This model uses numerical figures. Figures can provide a highly accurate result. It is therefore important to be precise, for example, when establishing the duration of a sound. Section 5.1.6 returns to the question of data accuracy.

\[ \text{[a]} \sim \text{[e]} \]
The vowel [a] is realised with a larger Intensity Integral Volume than schwa, due to the following physiological facts:

- As [a] is the most open vowel, the jaw makes a long movement, which takes a 'long' time;
- The [a] is an open vowel, with plenty of space for the vibrating air to escape from the mouth, causing a high intensity (dB).

De Graaf (1986, 4) mentions an average length of [a] of 115 ms. and an average length of [e] of 95 ms. for Modern Frisian. This difference in duration involves the X-axis in graph 5.1. This author's own recordings found an intensity proportion of [a] = 80dB : [e] = 75dB. Therefore, the [a] would be 115/95 times larger in its duration and 80/75 in its loudness than [e] = 1*(115/95)*(80/75) = 1.29.

Additional information has been obtained from the illustrations in Nooteboom & Cohen (1995, 128-136). From those pictures, the total
volume of duration and intensity can be measured. The ratio of the Intensity Integral Volumes of the second [a] in *java’s* and the final [ə] in *vaseline* is [a] : [ə] = 1.39 : 1. A similar case is provided by the [ə] in *kanon* ‘canon’ and the [ə] in *mate* ‘amount’, giving a ratio of [ə] : [ə] = 1.54 : 1. These two examples not only reflect the impact of quality contrast, but the word structures also differ. In both cases, the full vowel is followed by a consonant.

As an estimation, the average of the three described methods is taken: (1.29 + 1.39 + 1.54)/3 = 1.41.

Word-finality

Lunden (2006) studied the case of ‘extrasyllabicity’ of word-final consonants in Norwegian. There (and in other North Germanic languages) word-final syllables with one vowel and one consonant (= 2 morae) count as ‘short’ (cf. § 2.3.1). Lunden found that the reason for this is the fact that a word-final vowel is longer than a protected vowel, making the duration extension of an extra final consonant of 27% less noticeable (idem, 76). The extra duration from the additional consonant is partly obscured by a shorter vowel.

The outcome of her research is that in non-word-final position, the ratio between unstressed syllables CV : CVC is 1 : 1.6. As only the rhyme of the syllable counts, it is possible to establish the equation for non-final vowels. Note the following abbreviations:

\[ V_{nf} = \text{Non-final vowel, for example, the second /a/ in *makad* ‘made’}. \]
\[ V_f = \text{Final vowel, for example the /a/ in *seka* ‘cases’}. \]
\[ C = \text{Any word-final consonant, for example, the /d/ in *makad*}. \]

Expressing consonant duration as a ratio of the preceding non-final vowel:

\[ \frac{V_{nf} + C}{V_{nf}} = 1.6 \]
\[ V_{nf} + C = 1.6*V_{nf} \Rightarrow C = 1.6*V_{nf} - V_{nf} = 0.6*V_{nf} \]

Adding a consonant to a word-final unstressed vowel \( V_f \) gives a quantity increase of 27%, compared to a ‘standard’ CV-syllable. As soon at that is done, the vowel becomes a non-final vowel, so:

\[ \frac{V_{nf} + C}{V_f} = 1.27 \]

Substituting the outcome of equation (2) into (3) gives:
\( (V_{nt} + 0.6*V_{nt})/V_i = 1.27 \Rightarrow 1.6*V_{nt} / V_i = 1.27 \Rightarrow 1.6*V_{nt} = 1.27*V_i \Rightarrow 1.6/1.27*V_{nt} = V_i \)

i.e. an unstressed word-final vowel is \(1.6/1.27 = 1.26\) longer than an unstressed protected vowel. As this is about vowels of the same quality, no extra loudness factor is expected.

The multiplication factor for word-finality is 1.26.

**Preceding syllable length**

Section 2.1, which deals with Vowel Balance, presents observations from modern Dutch (Jongman & Sereno 1991, 296). The ending /\textit{on}/ in the long-rooted plural form \textit{taken} [t\textit{ako:n}] ‘tasks’ is on average 18% shorter than the same ending in the short-rooted \textit{takken} [t\textit{ako:n}] ‘branches’. This is the phonetic engine of all Vowel Balance features. From this, it is possible to establish a duration ratio of 100:82 = 1.22. Also here, the loudness effect is considered to be zero.

### 5.1.3 Making a forecast

A combination of two phonemes /\textit{a/} and /\textit{a/} with the two phonological contexts (protected ~ word-final; following long or short root) creates eight different contexts. In the rest of § 5.1 the following symbols for these contexts are used:

To mark the difference between word-final and protected vowels:

- \( \text{VC#} = \) unstressed vowel in word-final syllable in protected position, for example, \textit{makad}
- \( \text{V#} = \) unstressed vowel in word-final position, for example, \textit{wes\text{\textit{a}}}

To mark the difference between unstressed vowels (in bold) following a long or a short root:

- \( \text{V:C} = \) unstressed vowel following a long root, for example, \textit{f\text{\textit{o}re}}
- \( \text{VC} = \) unstressed vowel following a short root, for example, \textit{seke}

Observations from modern Germanic languages are made to quantify integral intensity differences in Old Frisian. The minimum size of the Intensity Integral is by default, one. The size of the Intensity Integral for the other sounds can be computed from the ratios defined in the previous section. For example, the sound with the smallest Intensity Integral Volume, a protected /\textit{a/} following a long root, has the default value of one. A word-final /\textit{a/}, following a short root has an Intensity Integral Volume of \(1*1.41*1.26*1.22 = 2.17\).
The simple product is an assumption. There is sufficient evidence that this score should not be interpreted on a linear scale. From several sources, it is known that human perception scales are not linear but logarithmic. For instance:

- Each octave jump in music is a doubling of tone frequency \( \log_2 \).
- The Mel scale, (a perceptual scale of pitches judged by listeners to be equidistant from one another), and the Equivalent Rectangular Bandwidth, a similar scale that expresses equidistant interpretation of pitches, are both conveyed with a formula, including a logarithmic component (Rietveld & Van Heuven 1997, 209 / 369-370)
- The decibel (dB) is a logarithmic unit of measurement that expresses the magnitude of a physical quantity.
- To obtain the visual sensation of equidistant grey tones in graphical design, a logarithmic scale must be applied (Bertin 1967).

These observations make it likely that the perception of the Intensity Integral Volume by the language listener follows a logarithmic, rather than a linear, pattern. Applying the ratios from § 5.1.2 produces the following relative Intensity Integral Volumes:

<table>
<thead>
<tr>
<th>example</th>
<th>vowel</th>
<th>finality</th>
<th>root quantity</th>
<th>score</th>
<th>( \log_{10}(score) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>bîleitb 'dies'</td>
<td>/ə/</td>
<td>VC#</td>
<td>V:CV</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>kamîth 'comes'</td>
<td>/ə/</td>
<td>VC#</td>
<td>V:CV</td>
<td>122</td>
<td>9</td>
</tr>
<tr>
<td>fîre 'for'</td>
<td>/ə/</td>
<td>V#</td>
<td>V:CV</td>
<td>126</td>
<td>10</td>
</tr>
<tr>
<td>kâpûd 'bought'</td>
<td>/a/</td>
<td>VC#</td>
<td>V:CV</td>
<td>141</td>
<td>15</td>
</tr>
<tr>
<td>seke 'case'</td>
<td>/ə/</td>
<td>V#</td>
<td>V:CV</td>
<td>154</td>
<td>19</td>
</tr>
<tr>
<td>bitâlîd 'paid'</td>
<td>/a/</td>
<td>VC#</td>
<td>V:CV</td>
<td>172</td>
<td>24</td>
</tr>
<tr>
<td>kâpîa 'to buy'</td>
<td>/a/</td>
<td>V#</td>
<td>V:CV</td>
<td>178</td>
<td>25</td>
</tr>
<tr>
<td>wësa 'to be'</td>
<td>/a/</td>
<td>V#</td>
<td>V:CV</td>
<td>217</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 5.1: Scores for the Intensity Integral Volumes of the vowel, based on extrapolation of modern phonetic measurements. The data is categorised according to computed scores.
If,
• The process of vowel reduction is an erosion of the Intensity Integral Volume;
and:
• The erosion is a purely quantitative process, in that it affects the volume of the Intensity Integral in a uniform way, irrespective of the kind of factors that contribute to it;¹⁴⁶,
then:
• The score in table 5.1 will be a prediction of the order in which the reduction will take place.

5.1.4 Checking the forecast
In this section, the forecast from § 5.1.3 is checked against historical data. Some remarks need to be made in advance. In some cases in chapter 2, geographical variations are observed. In these cases, the situation in the north-east will be the guide. In principle, any region would suffice, as long as it is a consistent choice. The choice of Middle Frisian data from the north-east has the advantage that it matches several sections of the codex *Unia*, in particular sections A-3, B and C, which were (re)written somewhere in the north-eastern half of Fryslân.

A second point is the fixation of the year of transition, for example, from [a] to [ə]. Chapter § 2 is an ongoing illustration of the fact that changes are gradual. Incidental modern forms often appear a long time before a sound transition was fully implemented. A long time after the shift, isolated older forms may still be attested. To pinpoint ‘the’ year of transition, this analysis attempts to establish the year in which modern forms become more than ± 10%, and the year in which older forms become less than ± 10%. The average of these two years is taken as the ‘year of transition’. Calculations are made on the basis of full decades.

V:C/ə/C# and VC/ə/C#
Finding a year for syncope of the protected /ə/ is difficult. There is a limited number of examples not traced back to the original /a/, such as *abbete* < *abbate* ‘abbot’. Most of the data from the charters concerns later instances of syncope, which were prohibited earlier by *wellformedness* constraints (graph 2.13). The process begins before the charter period, so the results rely on evidence from *Unia*.

The data about the syncope of protected /ə/ can be found in § 2.4.3.7 including

¹⁴⁶ This means, that if the Intensity Integral Volume of both vowel \(V_1 = x\) and \(V_2 = x\), both vowels will be reduced / deleted at the same time, even when the value of \(x\) is primarily dependant on the relatively long duration of \(V_1\) and the relatively high intensity of \(V_2\).
the case of syncope of verbal forms of the 3rd pers. sg. pres., such as *kumeth* '(he) comes' and weak past participles, such as *edêlêd* 'divided' (past. part.). Examples of an intermediate /<e>/ or /<i>/ following a short root appear in Unia groups A-1 and A-2. Vowel reduction was therefore not completed in Unia before 1350. Following a long root, vowel reduction must have happened prior to 1300.

In § 2.4.3.7 it is shown that syncope in Old Frisian *kumeth* 'comes' happened earlier than in *edêlêd*. From examples in Nooteboom & Cohen (1995, 128) it can be seen that the Intensity Integral Volume of an /a/ is greater when followed or preceded by voiced obstruents than by unvoiced ones. It is therefore possible to add even more detail to the description of the reduction process by including the voice of the context. For the forecast, the oldest figures from the 3rd pers. sg. pres. are used: the year 1300 for the syncope of /a/ that followed a long root and 1350 for the syncope of /a/ that followed a short root.

\[ V:C/a/C# \]

The summary of § 2.4.3.10 illustrates that apocope of the word-final /a/ following a long root starts in the late 14th century and is prevalent in various words by 1400, for example, in *för(e) *fore* 'before'. The /a/ is retained somewhat longer in the following circumstances:

- When the preceding consonant is a voiced obstruent, such as in *(mis)dêde* 'crime';
- When the final -e represents morphological information, as in *ic habbe* 'I have' and the dative singular masc./neuter in -e.

For the forecast the oldest instance of /a/-apocope from 1390 is used.

\[ V:C/a/C# \]

The /a/ following a long root is illustrated by examples as *habbath* 'have (pl. pres. ind.)' and *kâpad* 'bought (past. part.)'. The /a/ remained fairly dominant until the late 14th century but disappeared before 1430. The average between the year 1390 and 1430 is 1410. So this is the year used for the forecast.

\[ VC/a/C# \]

The word *seke* 'case' is a well-documented case of word-final /a/ following a short root. The form with final -e was dominant in the north-east until 1440 but had almost completely disappeared by 1460. The year for the forecast is therefore 1450.

\[ VC/a/C# \]

The case of a protected /a/ following a short root is illustrated by examples such as *bitalad* 'paid (past. part.)', *makad* 'made (past. part.)'. The examples from Unia
show only <a>, including the groups B and C. In the charters it was prevalent until 1440 and remained present in the north-east until about 1470, giving an average year of 1455. This is rounded off to 1460.

VC/a/ and VC:/a/.
The /a/ in word-final position was preserved until late in the 15th century. At that time, habba ‘to have’ had become a ‘short-rooted’ word, due to degemination of the consonants, but bitulla ‘to pay’ became a ‘long-rooted’ word (cf. § 2.5.2 and graph 2.20). The <a> was fairly resistant in the south, but in the north-east it disappeared in habba ‘to have’ and wesa ‘to be’ between 1490 and 1510, rendering the year 1500 for this overview. Graph 2.20 shows that in words such as bitulla ‘to pay’ and kâpia ‘to buy’, the reduction started some 20 years earlier, rendering the year 1480 for the forecast.

Table 5.2. shows the forecast from table 5.1 with an additional column containing the years defined in the above paragraphs. The correlation between the logarithm of the Intensity Integral Volume and the actual years of transition / vowel reduction is shown in graph 5.2. The correlation is high. Intensity Integral Volume values computed for original Old Frisian phonological settings are a fairly good basis for the prediction of developments over the next 200 years. The order of the changes is predicted by the values of the Intensity Integral Volume. When using the logarithm of the Intensity Integral Volume scores, the erosion of vowels appears to be an almost linear process. The linear development explains 95% of the observed variation ($r^2 = 0.95$; $p < 0.1\%$).

<table>
<thead>
<tr>
<th>vowel</th>
<th>quality</th>
<th>finality</th>
<th>root quantity</th>
<th>intensity integral score</th>
<th>log(score)</th>
<th>year</th>
<th>example</th>
</tr>
</thead>
<tbody>
<tr>
<td>[a]</td>
<td>&gt; [ə]</td>
<td>VC#</td>
<td>long</td>
<td>100</td>
<td>0.00</td>
<td>1300</td>
<td>bilîveth</td>
</tr>
<tr>
<td>[a]</td>
<td>&gt; [ə]</td>
<td>VC#</td>
<td>short</td>
<td>122</td>
<td>0.09</td>
<td>1350</td>
<td>kumeth</td>
</tr>
<tr>
<td>[a]</td>
<td>&gt; [ə]</td>
<td>V#</td>
<td>long</td>
<td>126</td>
<td>0.10</td>
<td>1390</td>
<td>fôre</td>
</tr>
<tr>
<td>[a]</td>
<td>&gt; [ə]</td>
<td>V#</td>
<td>short</td>
<td>154</td>
<td>0.19</td>
<td>1450</td>
<td>seke</td>
</tr>
<tr>
<td>[a]</td>
<td>&gt; [ə]</td>
<td>VC#</td>
<td>long</td>
<td>141</td>
<td>0.15</td>
<td>1410</td>
<td>kâpad</td>
</tr>
<tr>
<td>[a]</td>
<td>&gt; [ə]</td>
<td>V#</td>
<td>short</td>
<td>172</td>
<td>0.24</td>
<td>1460</td>
<td>makad / bitalad</td>
</tr>
<tr>
<td>[a]</td>
<td>&gt; [ə]</td>
<td>V#</td>
<td>long</td>
<td>178</td>
<td>0.25</td>
<td>1480</td>
<td>kâpia</td>
</tr>
<tr>
<td>[a]</td>
<td>&gt; [ə]</td>
<td>V#</td>
<td>short</td>
<td>217</td>
<td>0.35</td>
<td>1500</td>
<td>wesa</td>
</tr>
</tbody>
</table>

Table 5.2: Correlation between Intensity Integral values and years of vowel reduction.
A.P. Versloot: *Mechanisms of Language Change*

Mechanisms of Language Change

An example is nasalisation, a spontaneous phonetic process. In most languages, speakers tend to colour vowels preceding a nasal consonant. But, the ratio of nasalisation is variable. Actual levels of nasalisation can cover a wide range and in some languages, it is allophonic, while in others, it can be phonemic. When reconstructing an historical process where nasalisation is involved, parameter settings are unknown. When parameter settings can be deduced from a longitudinal retrospective approach, it is possible to accurately reconstruct the specific phonetic realisation of speakers from the past. This is an example of reverse engineering.

5.1.5 Reverse engineering: The final proof

So far, it has been illustrated that a combination of results from modern phonetic measurements and historical data match well. Values obtained by phonetic measurements enable a prediction of the developments, that can be verified in a retrospective approach. In a reversed approach, the phonetic details should be deducible from the historical figures. This may enable us to define historical phonetic details in cases where modern phonetic research returns ambiguous results or offers ranges of possibilities.

In § 5.1.4, the parameter settings are obtained from modern phonetic measurements. The parameter settings can also be deduced from historical data. For each of the three phenomena (contrast between [a] and [ə], word-finality and root quantity) the average year of vowel reduction can be computed:

---

An example is nasalisation, a spontaneous phonetic process. In most languages, speakers tend to colour vowels preceding a nasal consonant. But, the ratio of nasalisation is variable. Actual levels of nasalisation can cover a wide range and in some languages, it is allophonic, while in others, it can be phonemic. When reconstructing an historical process where nasalisation is involved, parameter settings are unknown. When parameter settings can be deduced from a longitudinal retrospective approach, it is possible to accurately reconstruct the specific phonetic realisation of speakers from the past. This is an example of reverse engineering.
As table 5.3 shows, the average year of reduction of \( \theta \) > \( o \) was 1373, while the average year of reduction from \( a \) > \( \theta \) was 1463. As this is an average and given all other phenomena are equally well represented, the difference of 90 years (1463 to 1373) is solely the result of a difference in vowel quality. The impact of word-finality is computed in a similar way:

### Table 5.3: Defining the average year of reduction for \( \theta \) versus \( a \)

<table>
<thead>
<tr>
<th>year of transition</th>
<th>( \theta ) or ( a )</th>
<th>example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300</td>
<td>( \theta )</td>
<td>biliveth</td>
</tr>
<tr>
<td>1350</td>
<td>( \theta )</td>
<td>kumeth</td>
</tr>
<tr>
<td>1390</td>
<td>( \theta )</td>
<td>före</td>
</tr>
<tr>
<td>1450</td>
<td>( \theta )</td>
<td>seke</td>
</tr>
<tr>
<td>1373</td>
<td>average for ( \theta )</td>
<td></td>
</tr>
<tr>
<td>1410</td>
<td>( a )</td>
<td>kâpad</td>
</tr>
<tr>
<td>1460</td>
<td>( a )</td>
<td>makad/bitalad</td>
</tr>
<tr>
<td>1480</td>
<td>( a )</td>
<td>kâpia</td>
</tr>
<tr>
<td>1500</td>
<td>( a )</td>
<td>wesa</td>
</tr>
<tr>
<td>1463</td>
<td>average for ( a )</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5.4: Defining the average years of vowel reduction in protected versus word-final position

<table>
<thead>
<tr>
<th>year of transition</th>
<th>V# or VC#</th>
<th>example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300</td>
<td>VC#</td>
<td>biliveth</td>
</tr>
<tr>
<td>1350</td>
<td>VC#</td>
<td>kumeth</td>
</tr>
<tr>
<td>1410</td>
<td>VC#</td>
<td>kâpad</td>
</tr>
<tr>
<td>1460</td>
<td>VC#</td>
<td>makad/bitalad</td>
</tr>
<tr>
<td>1380</td>
<td>average for protected position</td>
<td></td>
</tr>
<tr>
<td>1390</td>
<td>V#</td>
<td>före</td>
</tr>
<tr>
<td>1450</td>
<td>V#</td>
<td>seke</td>
</tr>
<tr>
<td>1480</td>
<td>V#</td>
<td>kâpia</td>
</tr>
<tr>
<td>1500</td>
<td>V#</td>
<td>wesa</td>
</tr>
<tr>
<td>1455</td>
<td>average for word-final position</td>
<td></td>
</tr>
</tbody>
</table>
The difference between word-final and protected position results in a difference of 75 years. The impact of the third phenomenon, the root length, can be calculated using a similar procedure. The average year for vowels following a long root is 1395. For vowels following a short root, it is 1440. The difference is 45 years. This method demonstrates a delay in vowel reduction due to the specific phonetic / phonological conditions.

To define phonetic properties of the phenomena involved from the past, the years of delay (90 - 75 - 45) relate to the duration of the total process. The first transition dates back to 1300, the last one to 1500. The transition years are those in the middle of the transition period, which covered around 30 years (cf. the discussion in § 5.1.4). The first transition started in 1300 - (30/2) = 1285 and the last one ended in 1500 + (30/2) = 1515, producing a total transition period of 230 years:

- A delay of 45 years refers to a total period of 230 years = 45/230 = 0.20.
- A delay of 75 years refers to a total period of 230 years = 75/230 = 0.33.
- A delay of 90 years refers to a total period of 230 years = 90/230 = 0.39.

A comparison of increase ratios from the historical data and from the modern phonetic measurements provides the following picture:

<table>
<thead>
<tr>
<th></th>
<th>ratio from modern phonetic measurements</th>
<th>ratio computed from the historical data</th>
</tr>
</thead>
<tbody>
<tr>
<td>[a] ~ [a]</td>
<td>41%</td>
<td>39%</td>
</tr>
<tr>
<td>V# ~ VC#</td>
<td>26%</td>
<td>33%</td>
</tr>
<tr>
<td>short ~ long root</td>
<td>22%</td>
<td>20%</td>
</tr>
</tbody>
</table>

Table 5.5: Measured and reconstructed phonetic increase ratios

The similarity is good, but not significant due to the low number of items ($r^2 = 0.74$, $p = 16.9\%$, one-tailed, $n = 3$). Using computed settings, instead of modern phonetic figures, to redraw graph 5.2 gives an even better match, with $r^2 = 0.96$ (was 0.95), but this is logical, as these figures are deduced from the same data. More important is that table 5.5 shows that historical data can be used to reconstruct the historical values of phonetic parameters.
5.1.6 Discussion
Four questions are considered in this section:

- How important are the exact figures?
- How is it possible that a linear erosion does not result in a uniform outcome: ø?
- How can the Intensity Integral Volume of 1300 have an impact over a period of 200 years?
- How does this deterministic model interact with other parts of the grammar?

How important are the exact figures?
In section 5.1.2, absolute factors for the impact of phonetic context (word-final versus protected etc.) are estimated from phonetic observations, while in 5.1.5 the values of those variables are computed by reverse engineering. The results can be found in table 5.5.

In phonology, contrasts are binary and not measured on continuous scales. The following graph 5.3 is a new version of 5.2, the difference being that binary scores have been applied. An /a/ gets one point, an /ø/ no points, a vowel following a short root one point, a vowel following a long root no points, and finally, one point for the word-final vowels, and no points for protected vowels. The maximum score is three for a word-final /a/ following a short root and the minimum is zero for a protected /ø/ following a long root. This is the outcome:

Graph 5.3: Correlation between summation of a binary phonological score and the timing of the vowel reduction
The relative order of the developments is not contradicted by the totals, but the fine-tuning is missing. The three items with a score of '1' follow point '0' in time and precede the '2' points score. However, the relative order of the three points with score of '1' can not be deduced from the binary phonological score. Binary phonological features, even when used as ordering entities, can not explain why syncope of protected /ə/, following a short root, as in Old Frisian *kumeth* 'he comes' precedes the reduction of /a/ > /ə/ in protected position following a long root, as in Old Frisian *kipad* 'bought'.

Linear erosion and non-linear outcomes

If there is a volume, eroded by a linear process, how it is possible that ultimately in some instances there is nothing left (/ə/ > ø), and yet in other instances there is still /ə/ < /a/? The expected outcome is that when 'mass' is eroded, all vowels end up at level zero, (with exceptions in cases where total syncope or apocope is prohibited by wellformedness constraints). This expected outcome is observed in for example, the East Frisian dialect of Wangerooge, and also in English. Old Frisian *hāwed*, *setta*, *mōnath* > Wangeroogic *hād*, *sēt*, *mōnt*, cf. Old English *heafod*, *settan*, *mōnath*, Modern English *head*, *set*, *month*. Why does Modern West Frisian have *baad* next to *sette* and *moanne*? The reason may reside in additional phonetic markings of the vowel by a pitch peak. A pitch peak can only be expressed through a vowel. Apparently, this results in the /a/ not being reduced to an ø, but staying as an /ə/ with a tonal peak.146 This was investigated in § 4.

The problem of collective linguistic memory

In § 5.1.4, in particular in graph 5.2, the reduction process is described as the linear erosion of the Intensity Integral Volume over 200 years, starting from late 13th century phonological configurations. Does this imply that speakers in for example, 1400, who had internalised (unconscious) knowledge of the phonetics of their time, knew about the phonetic properties of the language in 1300? This is highly unlikely.

The actual process is more complex than this linear degradation. Human speech organs and social conventions determine a fairly fixed range of vowel duration and loudness. There is a universal level of applicability in minimum length and loudness that is acoustically perceivable, while on the other hand, despite some cultural differences, the average loudness of utterances in any language, is compatible. The

146 This matches observations from Wangeroogic. Riustringen Old Frisian did not have a late pitch peak / L. Level Stress on a word such as *mōnath*, because of the long root. Short-rooted words such as *koma* 'to come' and *skipu* 'ships' had Level Stress and preserved their final vowel in Modern Wangeroogic: *kuum, schūnpu* (cf. Smith & Van Leyden 2007, p. 45 for the relationship between root quantity and Level Stress in Wangeroogic). Both in Wangeroogic and West Frisian, vowels with a pitch accent were preserved.
Intensity Integral Volume of all vowels is distributed over this fairly fixed range of duration and intensity. The sound at the bottom of the range is so weak, that it is often not heard by the (new) listeners and its reduction becomes a fact. By a process of self-organisation of vowel intensities, the remaining set of vowels is redistributed over the original range. At that moment, there is a new vowel at the bottom of the range, and the whole process is repeated. This is why reconstructed Intensity Integral Volumes from around 1300 provide a correct prediction of reduction order and time, but also why it is unnecessary to assume any kind of collective memory from the original figures.

In an experiment, the observation range has been shortened to the last six points, imagining that no older sources were available. The scores for the Intensity Integral Volume are redistributed over the same score range as the eight points from 1.00 to 2.17 used for the original scores. The result is shown in graph 5.4. The predictive power of the approach remains the same. Note that the year 1300 is an arbitrary point in time as well. Vowel reduction from older /a/ and /i/ > /a/ or even /, when following long roots (as in the long-rooted i- and u-stems, cf. table 2.2) or from /a/ > / in word-interior position (for example, bōdelis > bōdlis, table 2.21) had already taken place before 1300 and was probably controlled by the same mechanism. Therefore, the seemingly ‘collective linguistic memory’ is the result of ongoing interaction of speech organs, acoustics and speaker interactions, all of which are universal and constant over time.

Graph 5.4: Testing the working of the model during a shorter time frame, applying the same Intensity Integral Volume range from 1.00 to 2.17.
Interactions with morphology

The retention of Old Frisian /a/ as /a/ is already an indication that the linear reduction process could be blocked by other phonetic features. Morphology could also be a blocking factor. The word-final /a/ serves as an example here. Word-final /a/ appears both in Old Frisian dêde ‘deed’ and dêle ‘divided’. The former became Modern Frisian died or even die, with apocope of the /a/ and /d/, the latter is Modern Frisian divide, without apocope. The retention of the final /a/ enables a semantic contrast with the past participle. As the verbal ending /a/ still survives in modern language, this example illustrates that other phenomena in the language, in this case a semantic-morphological category, can counter phonetic tendencies.

The dative singular of masculine and neuter words have exactly the same word-final /a/ (§ 2.4.3.9). And indeed, while the /a/ in bitale, dore and dêde had disappeared by 1410, it survived until 1460/70 as a dative singular ending of masculine and neuter nouns. Why did it not stay longer than this, as was the case with the verbal ending? There is no obvious phonetic reason why it should collapse under the pressure of phonetic reduction, when the verbal ending did not.

Evidence from the noun skip is very illustrative (table 2.23):

- The old dative form, with Open Syllable Lengthening is /skipə/, written <schype>;
- The old form + apocope would return a new dative form */skip/, written *<schyp>;
- The attested new form in the syntactical dative context is /skip/, written <schip>.

The new forms without an -e which appear in a syntactic dative context in the late 15th century are not the old dative form minus [ə], but are leveled from the nominative/accusative: <schip>. This is an indication that it was not the phonetic / phonological development that caused the drop of the -e and hence the loss of the dative category. It was in fact the loss of the semantic / morphological dative category which resulted in the abandonment of the dative forms of -e. Definite articles in the language of the writer "Bogerman", from the first half of the 16th century, confirm the loss of the dative in the late 15th century. "Bogerman" uses a subject - object system in the definite article, for example, masculine subject (= nom.) <dy>, object (= dat. + acc.) <dan>, the latter being the form of the original accusative.149

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149 Bogerman actually uses three systems: Firstly, there are occasional appearances of old genitive and dative forms of all genders; Secondly, there is the subject - object system; Finally, there is a system that distinguishes gender only and not case, which is the situation found in the current dialect of Schiermonnikoog. The second system is dominant in Bogerman’s texts.
This order of developments is contrary to general assumptions in historical linguistics, for instance that it was the reduction of the endings that caused the collapse of the inflectional system (cf. § 1.2.5). Also in other languages, the abandonment of semantical or morphological categories preceeds the reduction of unstressed vowels. This can be observed in Swedish, Faroese and Wallisian High German. All these languages have at least as many full unstressed vowels and other possibilities to maintain an inflectional grammar as Icelandic. First the grammatical categories are abandoned, and then the endings are lost.\footnote{150}

In early-Modern Frisian, the petrified historical dative form <‘t schijp> (no longer perceived as a functional dative) is attested, suggesting that /æ/ apocope could take place in this context. In the interaction between phonetic reduction tendencies and the semantic-morphological concept of ‘dative’, the latter won. But as soon as the dative had been abandoned, the phonetic erosion continued its ‘attacks’, and the final /æ/ in *te skipe was easy prey, just as in another petrified dative yn ’e hûs < in da hûs ‘in the house’. The final /æ/ was retained in a third petrified dative formula in Modern Frisian: yn ’e (lytte) loege < in da loge\footnote{151} The word loege is limited to this idiomatic expression, so there is no attraction from *loech. The retention of the final /æ/ was supported by phonetical reasons: The neighbouring voiced /γ/ enlarged the Intensity Integral Volume of /æ/ (cf. § 2.4.2).

The interaction of speaker strategies, phonetic tendencies and morpho-semantic categories is illustrated in the bidirectional simulation model in § 5.2.

\footnote{150} The question ‘why’ with respect to this development cannot be answered here. It is presumed that this has to be found in the interaction between syntax and semantics.

\footnote{151} As the word is only attested in this fixed expression, this old neuter word is now perceived as a word of common gender, taking the article de / enclitic ’e (Hoekstra and Visser 1996, 72).
5.1.7 Concluding remarks

The successful application of this deterministic model of language change does not pretend to be the panacea for all questions concerning sound reduction. Complicating factors, such as wellformedness, tone contours and morphology illustrate that, in the overall language system, these simple linear correlations are not the only issues. However, compared with the frequently expressed agnostic position on language change (cf. for references Zuraw 2003, 139), this model does constitute a relative advance in the understanding of ‘why’ languages change.

Correlations found in this section are not only those which can be attributed to chance. The model is more than a descriptive, well-functioning ‘black box’. The high correlation between the Vowel Intensity Integral and the temporal order of the vowel reduction, provides evidence of a causal relationship between them. In a reductionistic approach, the components are from the real world, their interactions are causal and their validity is proven outside the actual field of application. The results of this section expand on:

• Repeatable, acoustic observations, which depend on features such as muscular motion, and actual acoustics which obey the laws of physics;
• The applied logarithmic ordering of perception scales, widely attested outside the field of linguistics.

At the same time,

• The results match observations from random language utterances (in written form). Any possible subjective intuition on ‘grammaticality’ by the researcher is avoided.

Section summary:

• The reduction of unstressed vowels in West Frisian between 1300 and 1550 shows a very high correlation with the reconstructed Vowel Intensity Integrals of the vowels in question;
• This high correlation provides evidence of a causal relationship between Vowel Intensity Integral and the reduction process;
• As deterministic processes rely on causal relationships, this reconstruction provides evidence of a deterministic character of language change.
5.2 A bidirectional model of language change

In § 1.4, *acoustics/articulation, meaning* and the general working of the *human mind (memory)* are mentioned as the three keystones of a deterministic system of language. Section 5.1 is an illustration of the impact of articulatory convenience and acoustics. These tend to erode any language system. Without counter forces, this would lead to a total degradation of language utterances. This tendency is countered, however, by the demand for effective communication. In the balance between functional communication and convenience\(^\text{152}\), people do not instantly apply the minimum effort possible, with only the restriction of communicating, they are also bound by seemingly inconvenient, social conventions.

Society is full of activities which cost people a great deal, but are not particularly good for them as individuals. These activities are performed because ‘our neighbour is doing it as well’. To give an example from language: All grammatical persons of the verb in English can do without any specific marker. There is no misunderstanding with: “he sing” or “she make”. Some English learners do so, and they are understood perfectly well. However, with the exception of learners, people avoid making this mistake, because this is not how they learned the language and, moreover, it would sound silly speaking in such as way. The choice between “she make” or “she makes” is not random. Instead of being driven by constraints on the linguistic effect, it is driven primarily by constraints on the social effect, which apparently overrule the minimum linguistic system requirements. Individuals are storing in their memory both linguistic and context information, such as social conventions and individual circumstances (cf. Port & Leary 2005, 954-955). For this section, it is enough to signal that people take note of common practice when producing their own language.

Frequency figures are a suitable quantifier of the concept ‘common practice’. Neurological and cognitive sciences indicate that frequency is not only an abstract numerical expression of ‘common practice’, but it is also an actor in the formation and structuring of our memory. This basic function of the brain is used in Oudeyer (2005) for example, in his modelling of the growth of vowel systems through self-organization. Bare frequency may be a somewhat crude component, however neural research is a hot topic currently and future results from such research will contribute further to the understanding of memory formation, also with respect to

\(^{152}\) ‘Functional communication’ resembles the Faithfulness Constraints, and ‘convenience’ matches Markedness Constraints in *Optimality Theory*. 

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language data.\footnote{Frequency alone is probably not enough. One example of another effect is ‘priming’, but there are definitely more. Priming means that an item passed recently is more likely to be re-applied than an older one. Priming effects have been studied on different time scales.}

The following section, 5.2.1, introduces the Bidirectional Table and explains how the three factors of phonetics (articulation and acoustics), meaning (semantics) and memory (taking notice of ‘common practice’) are represented in it.

Section 5.2.2 shows which predictions this model makes for the vowel reduction in the case of contrasting morphological endings. Morphological categories, such as singular and plural, or 1st person singular versus infinitive, are projections of the real world: the difference between one dog or two dogs is just as much a categorical interpretation of real world phenomena as the categorical contrast between a ‘dog’ and a ‘cat’, and hence a form of semantics. In § 5.2.3 the results will be compared with the actual developments in the language of the Middle Frisian charters for the pair habbe, 1st pers. sg. pres. ~ habba, infinitive of ‘to have’. In § 5.2.4, the example of the singular seke ‘case’ versus the plural seka/ seken is assessed.

5.2.1 Introducing the Bidirectional Table\footnote{For the content of this chapter, the author is highly indebted to the work of Paul Boersma, whose lecture at the Jadertine Summerschool in Zadar, September 2006 inspired the consideration of algorithms for the formation of grammatical structures and the concept of bidirectionality (cf. Boersma 2006, Boersma & Hamann 2006). The supervisors of this thesis presented the challenge to transform the criticism of traditional phonological theories into a working approach in linguistics. It was later discovered that the resulting new concept of the Bidirectional Table has a full counterpart in Ke’s Probabilistic Learner (2004, 141 ff.)}

This first example illustrates the effectiveness of the Bidirectional Table, comparing the phonological contrast of the final /a/ and /a/ in the verb habba. The infinitive regularly appears with the final <a> in Old Frisian (cf. § 2.4.3.5). The regular historical appearance of the ending of the 1st pers. sg. pres. is <e> (§ 2.4.3.9). The early-Modern Frisian form of the 1st pers. sg. pres. is hab, with syncope. When followed by the clitical pronoun (habb’ ik), apocope becomes faster than in other contexts. Apparently here, a syntactic structure is interfering. The same holds for the frequent form of the 1st pers. pl. pres. with clitic: habba wi < habbath wi. These figures have been left out of this example, to enhance the picture. The effectiveness of the Bidirectional Table was then checked, including all data in the 1st pers. sg. pres and all instances of both the infinitive and pl. pres. tense forms without a final <t(h)>. The observed patterns remain the same, but the calibration data (see § 5.2.3) change slightly (no further treatment).
Over the period 1390 to 1430, the following verbal endings have been attested and are not followed by a clitical pronoun:

<table>
<thead>
<tr>
<th></th>
<th>1390-1430</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ø</td>
</tr>
<tr>
<td>1st sg</td>
<td>1</td>
</tr>
<tr>
<td>inf</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.6: Number of written endings in the original charters from 1390 to 1430 detailing the 1st pers. sg. present and the infinitive of habba 'to have'

This table shows that there are six attestations to the 1st pers. sg. pres. of <habbe> and one of <hab>. The infinitive is written <habba> six times and <habbe> once. Note that these are real figures from the charters. The classical forms (1st pers. sg. pres. habbe and inf. habba) are dominant. The consequence of the evaluation of the charter data in § 1.3 and chapter 2 is that figures in table 5.6 can be taken as a reliable reflection of the linguistic reality of that time. The contrast between the 1st pers. sg. pres. and the infinitive for the endings <e> and <a> is statistically significant.

There are a number of circumstances that may cause an inaccurate perception to the listener of some unstressed vowels. These include:

- In faster speech, vowels are realised with a reduced formant contrast (cf. De Graaf 1986, 18), a manifestation of the speaker's convenience tendency;
- The stress pattern of a sentence may place relatively little emphasis or energy on the unstressed vowel;
- There may be disturbing background noise;
- The listener may have a less than sharp ear;
- The listener's attention may be flawed;
- etc.

Wherever it happens, somewhere between the speaker's intended prototype and the listener's final interpretation, something causes the listener to perceive a reduced version of the vowel, for example, [وغ] instead of [أ]. By chance, this may also work in the opposite way, where a listener hears something that he interprets as an /أ/ while an /غ/ was intended. In vowel contrast reduction in allegro speech (cf. the mentioned study De Graaf 1986), acoustic and environmental noise can cause skewed deviations. The probability of an intended /غ/ being perceived as an /أ/ is greater than that of it being perceived as an /أ/. This skewed distortion effect can be found in the table. There is a secondary appearance of an /أ/ as an ø, while instances of /غ/ as an <أ> are missing in table 5.6. For /أ/, a similar,
‘downgrading’ leak is found from /a/ to /ə/. This disturbing acoustic and perceptual effect is referred to as ‘noise’ in the following paragraphs.

From an absolute number of forms, production ratios have been calculated.

<table>
<thead>
<tr>
<th>1390-1430</th>
<th>ø</th>
<th>&lt;e&gt;</th>
<th>&lt;ə&gt;</th>
<th>production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st sg</td>
<td>1</td>
<td>6</td>
<td>0</td>
<td>14% 86% 0%</td>
</tr>
<tr>
<td>inf</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>0% 14% 86%</td>
</tr>
</tbody>
</table>

Table 5.7: Production ratios for full and reduced forms during the period 1390 to 1430

On the right hand side of table 5.7 production ratios of alternative verbal forms are shown. Six out of seven cases of the 1st pers. sg. pres. are formed with an <e>, which equals 86%. There is one case with no ending, representing 14% of the attestations. The sum of the cells in row one is 100% (horizontally). It is mutatis mutandis the same for the infinitive in the second row. The production figures represent the speaker’s perspective. They constitute a ‘common practice’ for all speakers. If a speaker wants to speak ‘normally’, he would prefer the use of [hab:ə] in the 1st pers. sg. pres., etc., but occasional realisations of [hab] are not ridiculous. It would, however, sound ‘exaggerated’ to use only [hab].

In a bidirectional approach, there is also the listener’s perspective. Being confronted with the form [hab:ə], there can be no doubt about the speaker’s intended meaning: [hab:ə] can be nothing else but an infinitive. Hearing [hab] is an unambiguous listener’s cue for the interpretation as a 1st pers. sg. pres. Hearing [hab:ə], the listener has to overcome some ambiguity. Six out of seven instances of <habbe> in the charters from the period 1390 to 1430 are used as a 1st pers. sg. pres. The interpretation of [hab:ə] is that the speaker most likely (six out of seven or 86%) wants to express a 1st pers. sg. pres., but the possibility of an infinitive must also be considered (one out of seven or 14%). This perception is shown in additional cells at the bottom of the table. The sum of the cells in each column is 100% (vertically):

---

**Note:** The repeating cell values of ‘6’ and ‘1’ are purely coincidental. These are absolute token numbers from the charters.
Table 5.8 shows that for example, 14% of the actually produced forms of a 1st pers. sg. pres. in the speakers’ community are [hab] and that their interpretation by listeners is unambiguous. This form is 100% reliable. The same 1st pers. sg. pres. is realised as [hab:a] in 86% of the cases and a listener, being confronted with this form, will be fairly sure (86%) that he is dealing with a 1st pers. sg. pres., etc. This implies that there is a tension in the 1st pers. sg. pres. between the common form [hab:a], and the semantically optimal form [hab]. For the infinitive, no similar tension is at stake. The secondary, reduced form of [hab:a] is not a reliable realisation of an infinitive (14% reliability) and new speakers will not become attracted to it.

Table 5.8 contains all three components mentioned:

- The acoustic properties are represented by the adjacent positioning of ø ~ [o] and [o] ~ [a], with a default skewed ‘leak’ to the left;
- Semantic aspects are expressed by perception / reliability ratios at the bottom;
- The memory component is expressed by production ratios on the right of the table: Which form has the highest frequency and suits the common practice?

5.2.2 Turning the table into a working algorithm

Which variant will speakers choose and how does this affect the development? What are the production strategies and how do they influence perception strategies? For this model, there is no extra-linguistic preference for any of the forms (for example, some educational standardisation) nor additional phonological or phonetic factors which may favour any variants.

The algorithm is based on the habbe-habba case, but now the table starts with an idealised Old Frisian situation: 1st pers. sg. pres. (‘1st sg.’) -e, infinitive -a. Because the number of attestations in each row affects reliability ratios in the columns, it is important to use proper numbers for both paradigm forms. From the database over the entire period studied, a proportion of 1.4 : 1 can be deduced for the ratio of
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1st sg : inf. In the idealised model, there are no secondary forms and every form is 100% in both production and perceptual reliability. The situation in table 5.9 contains no tension whatsoever and is not likely to change.

<table>
<thead>
<tr>
<th>stage 1</th>
<th>1st sg</th>
<th>inf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ø</td>
<td>&lt;e&gt;</td>
</tr>
<tr>
<td>1st sg</td>
<td>0</td>
<td>140</td>
</tr>
<tr>
<td>inf</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>perception</td>
<td>0%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 5.9: Idealised Bidirectional Table: Stage one

The next step is to introduce noise. Noise levels might be deduced from experimental phonetic research, but this example refers to an early 14th century situation with 14% reduced forms. A noise reduction ratio of 10% is assumed, i.e. 10% of the cases where [a] is meant by the speaker but heard as [ø] by the listener. The probability of noise working the other way around (i.e. an intended [ø] being understood as [a]) is much lower. An ‘upgrading’ noise ratio of 1% is also assumed. The result of the implementation of this noise factor is found in the stage two table:

<table>
<thead>
<tr>
<th>stage 2</th>
<th>1st sg</th>
<th>inf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ø</td>
<td>&lt;e&gt;</td>
</tr>
<tr>
<td>1st sg</td>
<td>14</td>
<td>125</td>
</tr>
<tr>
<td>inf</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>perception</td>
<td>100%</td>
<td>93%</td>
</tr>
</tbody>
</table>

Table 5.10: Bidirectional table with application of noise: Stage two

Following the noise factor, 10% (=14) of the 1st sg cases of an intended [ø] are now realised in such a way that they are perceived as ø, while 1% (=1) is realised / perceived as [a]; mutatis mutandis for the infinitive forms, without the possibility of ‘upgrading’.

The next step is to determine the speaker’s choice for either of the variants. Social conformity by the speaker in using ‘common practice’ favours the choice of the

---

In the table, the absolute frequencies of 140 and 100 are used. They are only a measure of the ratio 1st sg : inf. Instead of 140 : 100, it would also be possible to use figures such as 70 : 50 or 1400 : 1000. For the early-Modern Frisian data, the ratio is also exactly 1.4 (including correction for the inverted word order *hab ick*).
most common form. For the 1st sg., that would be hābbe. If perception were the only leading force, the less ambiguous forms should be chosen: In the 1st sg. that would be hāb. It is almost impossible to predict the choice of one speaker in one utterance: In the 1st sg., the speaker will simply say [habːə] or [hab]. Here, the power of the large numbers offers a way-out. Throwing a die once, will return a ‘3’ or another number. The outcome is a binary event (it either happens or it doesn’t), even though the probability of a ‘3’ is 1/6. When throwing a die 100 times, approximately 17 throws will be a ‘3’, as 17/100 = 1/6. When an event is highly frequent, the probability ratio and actually observed values approach each other. A production ratio of 10%, apparently reflects an underlying probability factor of 10%. The probability factor equals the actual distribution ratio. For this model, it is assumed that the observed form frequencies reflect the overall frequencies in daily live speech and, therefore, the underlying probability factors.

The choice between the two variants is controlled by two desires which can both be expressed by probability factors:

- The desire to speak ‘normally’, to conform with common practice:
  - to say [habːə] as the 1st pers. sg. represents an accommodation to the common practice of 89%;
- The desire to be understood, to use unambiguous forms:
  - to say [habːə] as the 1st pers. sg. means that the signal is unambiguous for 93%.

Combining two probability factors is usually expressed by multiplying the factors. It is assumed that people are guided equally by common practice and the reliability of the signal towards the listener. Now, the probability of [habːə] as the 1st sg. can

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157 The probability of throwing a ‘3’ with a die can be deduced from the number of faces on the die; six, so there is a 1/6 chance. But the die can be thrown 1000 times and the number of times it lands on three is about 167. This reveals a 167/1000 chance or 1/6 ratio (cf. Moore & McCabe 2003, 283).

158 Take a combination of a letter and a number, for example, A3 or T8. The probability of guessing it right is 1/26 (for the letter) times 1/10 (for the number) = 0.038 %, as there are 26 different letters and 10 different numbers (0-9).

159 The model was tested for other ways of computation, for example to apply the square of the production and perception factors, which favours frequent and/or reliable variants. Applying the square of the production probability causes the system to come to a standstill, with the persistence of the historical forms as a result. This may reflect a situation of a strong norm, for example societies with high levels of literacy, such as modern European countries, but also Iceland in earlier ages. Further testing of this kind of extensions to the model is definitely worthwhile.
be computed as: $0.89 \times 0.93 = 0.83$. The choice of the form \([hab] = 0.1 \times 1 = 0.10\), while the choice of \([hab:a] = 0.01 \times 0.02 = 0.0002 = 0.00\), etc.

<table>
<thead>
<tr>
<th>stage 3</th>
<th>(\emptyset)</th>
<th>(&lt;\varepsilon&gt;)</th>
<th>(&lt;\alpha&gt;)</th>
<th>production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st sg</td>
<td>14</td>
<td>125</td>
<td>1</td>
<td>10% 89% 1%</td>
</tr>
<tr>
<td>inf</td>
<td>0</td>
<td>10</td>
<td>90</td>
<td>0% 10% 90%</td>
</tr>
<tr>
<td>perception</td>
<td>100%</td>
<td>93%</td>
<td>2%</td>
<td>10% 83% 0%</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>7%</td>
<td>98%</td>
<td>0% 1% 89%</td>
</tr>
</tbody>
</table>

Table 5.11: Bidirectional table with calculation of the new production ratios, based on the multiplication of the production and the reliability ratios.

Note that the sum of the row of probabilities has become less than 100%; in the first row: $0.1 + 0.83 + 0.00 = 0.93$. In order to compute new production figures, this has to be corrected. The total number of tokens must remain the same. To compute the new production figure for \([hab]\) as a 1st sg., the new production probability needs to be divided by the sum of the new production probabilities and multiplied by the number of tokens: $(0.1/0.93) \times 140 = 15$ tokens. For the form \([hab:a]\) this is: $(0.83/0.93) \times 140 = 125$ tokens while for \([hab:a]\) it is: $(0/0.93) \times 140 = 0$ tokens. The same calculation can be done for infinitive forms. This results in the sum of tokens in all cells remaining at 240. The result is shown in table 5.12.

<table>
<thead>
<tr>
<th>stage 4</th>
<th>(\emptyset)</th>
<th>(&lt;\varepsilon&gt;)</th>
<th>(&lt;\alpha&gt;)</th>
<th>production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st sg</td>
<td>15</td>
<td>125</td>
<td>0</td>
<td>11% 89% 0%</td>
</tr>
<tr>
<td>inf</td>
<td>0</td>
<td>1</td>
<td>99</td>
<td>0% 1% 99%</td>
</tr>
<tr>
<td>perception</td>
<td>100%</td>
<td>99%</td>
<td>0%</td>
<td>1% 100%</td>
</tr>
</tbody>
</table>

Table 5.12: Bidirectional table with new intentional production figures and corresponding perception ratios.

For the infinitive, the noise factor in stage two (table 5.10) produces 10 instances ($= 10\%$) of forms that were meant as an \([a]\), but perceived as an \([\varepsilon]\). In table 5.12, it is shown that speakers are inclined to produce the infinitive form \([\varepsilon]\) in only $1\%$ of the cases. So, a form resulting from noise and causing ambiguity is cleaned up by this algorithm. This is exactly what should be expected from a functional communication system. There is no need for an explicit rule or constraint in the language stating that \([hab:\varepsilon]\) as an infinitive form would be prohibited. Actually, the form is not prohibited, it is discouraged. Where the algorithm confirms the position of \([hab:a]\) as an infinitive form, it goes a different way in the choice between the
singular forms [hab] and [hab:a]. The unambiguous form of [hab] is gaining ground, albeit only marginally (from 10% to 11%). The infrequent and semantically unattractive 1st sg. form [hab:a] is swept away (< 0.1%).

The combination of being faithful to tradition (conforming to common practice and social behaviour) and the semantic intention of the speaker ensure the functionality of the system, even in a setting of continuous phonetic noise.

Now that the newly intended production figures are calculated, the same circle is entered again, because 10% (cf. commentary to table 5.10) of the cases of the 1st sg. habbe, intended as [hab:a], will reach the brain of the listener as [hab], due to noise. This means that the intended 15 cases of [hab] as the 1st sg., mentioned in table 5.12, are joined by 10% of 125 cases (= 12), intended as [hab:a], but perceived as [hab] due to noise. This brings the total of [hab] to 15 + 12 = 27. Applying the above-mentioned noise factors to the other cells as well, enables a new production / perception table to be prepared:

<table>
<thead>
<tr>
<th>stage 5</th>
<th>ø</th>
<th>&lt;e&gt;</th>
<th>&lt;a&gt;</th>
<th>production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st sg</td>
<td>27</td>
<td>111</td>
<td>1</td>
<td>20% 79% 1%</td>
</tr>
<tr>
<td>inf</td>
<td>0</td>
<td>11</td>
<td>89</td>
<td>0% 11% 89%</td>
</tr>
</tbody>
</table>

| perception | 100% | 91% | 1% |
|            | 0%   | 9%  | 99% |

Table 5.13: New production ratios from table 5.12, now including phonetic noise.

This procedure can be repeated time after time, producing a series of tables. After 16 complete runs, the situation is as follows:

<table>
<thead>
<tr>
<th>stage 5</th>
<th>ø</th>
<th>&lt;e&gt;</th>
<th>&lt;a&gt;</th>
<th>production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st sg</td>
<td>139</td>
<td>1</td>
<td>0</td>
<td>99% 1% 0%</td>
</tr>
<tr>
<td>inf</td>
<td>2</td>
<td>27</td>
<td>71</td>
<td>2% 27% 71%</td>
</tr>
</tbody>
</table>

| perception | 98% | 6%  | 0% |
|            | 2%  | 94% | 100% |

Table 5.14: New production rates after 16 runs, including the application of phonetic noise (stage five of the loop).

At this stage of the process the number of realisations of the 1st sg. as [hab] gradually increases and reaches almost 100%. The appearance of [hab:a] is solely
the result of the noise factor.\textsuperscript{160} Table 5.14 is not yet in equilibrium; after 45 complete runs, the figures are as in table 5.15:

<table>
<thead>
<tr>
<th></th>
<th>ø</th>
<th>&lt;e&gt;</th>
<th>&lt;a&gt;</th>
<th>production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1\textsuperscript{st} sg</td>
<td>139</td>
<td>1</td>
<td>0</td>
<td>99%</td>
</tr>
<tr>
<td>inf</td>
<td>7</td>
<td>60</td>
<td>34</td>
<td>7%</td>
</tr>
<tr>
<td>perception</td>
<td>95%</td>
<td>2%</td>
<td>0%</td>
<td>60%</td>
</tr>
</tbody>
</table>

Table 5.15: New production rates after 45 runs, including the application of phonetic noise (stage five of the loop).

The 1\textsuperscript{st} sg. reaches its final position already in table 5.14, but in the meantime, the infinitive starts to shift from predominantly [hab:a] to predominantly [hab:a]. The system reaches an equilibrium after 64 runs, with the infinitive [hab:a] calculated at 62%.

5.2.3 Verifying the model

Relative order predicted by the model

The verification of the model starts with the evaluation of the general trend. Section 2.4.3.9 assesses the development of the 1\textsuperscript{st} pers. sg. pres. habbe. The ending <e> starts to vanish in around 1430 and has disappeared by 1460. Note that this is later than expected from a purely phonetic reduction process point of view, (discussed in § 5.1). The word-final /ø/ following a long root in, for example, for 'before' has already disappeared by 1400. In accordance with the order predicted by the algorithm in § 5.2.2, the reduction of the infinitive ending from [a] to [æ] first starts after the completion of the reduction of the 1\textsuperscript{st} pers. sg. pres. [hab:a] > [hab], i.e. not before 1490, cf. § 2.4.3.5. Where the algorithm reaches an equilibrium after 64 runs with still 31% [haba], both graph 2.10 and map 2.11 show that the final [a] in the infinitive was indeed ‘reluctant’ to disappear completely. This transition takes much longer than the reduction of the 1\textsuperscript{st} pers. sg. pres. habbe.

Absolute order predicted by the model

The real data can also be used to see if the relative order, predicted by the model and confirmed by the data, has any absolute implications. The transition period of

\textsuperscript{160} It is questionable if the ‘upgrading noise’ from ø > [æ] indeed equals the ‘upgrading noise’ from [a] > [æ]. Both have the value 1% in this model. The model can also run assuming that a sound which has disappeared cannot be revealed again, therefore setting the ‘upgrading noise’ from ø > [æ] at 0%. The difference is that exactly the same configuration of table 5.14, apart from 1 x <e> in the 1\textsuperscript{st} sg., is reached after 14 runs instead of 16.
A dissertation by Bart de Boer (2006) indicates that the creation of vowel systems with a limited number of phonemes in acoustic continuum can be modelled by self-organisation. The development from [hab:a] to [hab] takes 30 years, from 1430 until 1460, represented by 15 runs in the model. This implies that 1 run represents 2 years in real time. Applying this calibration to the infinitive data returns the following figures: Near equilibrium is reached after 45 runs, representing 45 * 2 = 90 real time years. Adding 90 to the beginning of the entire process, the year 1430, becomes 1520. Between 1510 and 1550 <habba> is found as an infinitive in 39% of the attestations, being strikingly near to the predicted 34% from the model.

The final transition from /a/ to /a/

What this version of the model does not describe, is the final clean-up of the ending [a], which must have taken place before the end of the 16th century. In late 16th-century sources from early-Modern Frisian, the ending <a> is absent in contemporaneous texts. In the north, the transition process finishes prior to 1510. In the late 15th century there is only one phoneme /a/, with a prototypical realisation of [a] and a high tolerance for a more open distribution [a] in some contexts (cf. § 3.3, table 3.2). Additional algorithmic modelling is needed to simulate the actual concentration of realisations closer to [a]. Another flaw of this model is that it only presumes the phonetic stages ø, [a] and [a], while the entire range is an acoustic continuum.

The detailed course of the development.

The previous discussion shows that both the predicted relative order and the predicted absolute speed of the development match the order and timing of the historical developments. The most intriguing aspect in the habbe-habba case is the form [hab:a]: In Old Frisian, this was the main form of 1st pers. sg. pres, but in early Modern Frisian, it was the prototype (as [haba] after degeminisation) of the infinitive. How does the language deal with meaning-form ambiguity in the model and does it match the real data?

Table 5.16 shows observed and computed data for production and perception reliability ratios of <habbe> as the 1st pers. sg. pres.:
The match between the computed and the observed data is high, with $r^2 > 0.9$ and $p < 0.1\%$, making it highly likely that both datasets are drawn from the same underlying dataset. The relationship between production and perception reliability can be shown in a two-dimensional graph, with production on the X-axis and perception scores on the Y-axis. The black points in graph 5.5 show the observed values from 5.16. The open points connected with a dashed line are based on computed data.

Graph 5.5: Relationship between production and perceptional reliability ratios of <habbe> as the 1st pers. sg. pres. of habba, comparing observed data in the charters with the computed data from the Bidirectional Tables.
For <habbe> as the form of the infinitive, the table is as follows:

<table>
<thead>
<tr>
<th>&lt;habbe&gt; inf</th>
<th>Observed</th>
<th>Computed</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1430</td>
<td>14%</td>
<td>14%</td>
</tr>
<tr>
<td>1430-1460</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>1460-1490</td>
<td>9%</td>
<td>71%</td>
</tr>
<tr>
<td>1490-1510</td>
<td>28%</td>
<td>93%</td>
</tr>
<tr>
<td>1510-1550</td>
<td>63%</td>
<td>95%</td>
</tr>
</tbody>
</table>

Table 5.17: Observed and computed produ(uction) and perc(ption reliability) ratios for <habbe> as a form of the infinitive habba

The correlation between observed and computed production is rated less than in the previous table, but is still strong with $r^2 = 0.48$, while the p-value of the one-tailed test is 9.8%. However, for perception, the levels are the same as in table 5.16 ($r^2 = 0.92$, p = 0.5%). The graphical depiction of this data is found in graph 5.6. Note that the temporal direction of the curves in 3.6 and 3.7 is reversed. In graph 5.5, the points near the 0-0-point are the youngest ones, while in graph 5.6 the points from the oldest data are close to the 0-0-point. The graph shows that the course of the development is well predicted. The low correlation of production rates is the result of a different timing, not an incorrect sequence.

Graph 5.6: Relationship between the production and perceptional reliability ratios of <habbe> as an infinitive of habba, comparing observed data from the charters with computed data from the Bidirectional Tables.
Both graphs illustrate the ability of the language to overcome the problem of semantical ambiguity. First, the production rate of the ambiguous form of the 1st pers. sg. pres., <habbe> drops, while its perceptual reliability is still high, for example, in table 5.16, time frame 1430 to 1460: Production of the 1st sg. form [habə] is 37%, the perceptual reliability is 97%. Subsequently, in the following time frame, the perceptual reliability also falls, reaching very low levels for both aspects after 1490. As a realisation of the infinitive, <habbe> is initially infrequent and unreliable. Between 1460 and 1490, the reliability improves drastically. It is then that it becomes an interesting form for speech production. Production reaches > 60% in the last time frame.

**Concluding remarks**

The algorithm using the Bidirectional Table, modelling speakers’ strategies by multiplying the production ratio by the perceptual reliability, provides a fairly good estimation of the development of [habə] - [habə] towards [hab] - [habə]. Both the relative and the absolute order of developments can be predicted from the model.

It is particularly worth noting that a speaker’s attitudes towards aspects of ‘common practice’ and communication effectiveness do not change over time, nor do phonetic noise levels. This is an essential characteristic of any algorithmic approach (cf. § 1.4). However, constant attitudes and values predict the non-linear course of the developments as depicted in graphs 5.5 and 5.6. Trying to describe this part of a speaker’s grammar, including observed variations, with something like a ‘rule’, would demand:

- Continuous adjustment of the rules, describing variations from year to year,

alternatively, where a static rule with a statistical component is used:

- Continuous adjustment of statistical components.

In both cases, neither the direction nor the velocity of the adjustments can be predicted. In this model, speakers’ attitudes, i.e. their intention to produce ‘grammatically’ correct utterances, remain constant. It is the deterministic interaction of reductionistic components which causes shifts in language production.

The choice of the three components: ‘articulatory convenience’, ‘common practice’ and ‘effective communication’ as the actors in a causal relationship receives support from the working of the model.
5.2.4 A second case study: seke

The effectiveness of the algorithm has also been tested on data from the noun seke ‘case’, Old Frisian singular form seko, nom./acc. plural seka. The description of the developments in the charters can be found in § 2.4.3.4 and § 2.4.3.8. To summarise the developments again:

- North-East: singular: \( seko > sek \) between 1440 and 1460
  plural: seka remains stable until at least 1490; -a is quickly replaced by the new ending -en in the late 15th century;
- South & west: singular: seke remains dominant until 1470
  plural: seken appears in around 1440 and gradually takes over during the next 30 years.

Developments in the region North-East

Developments in the North-East, with the -e / -a contrast acting as an engine for them, are very similar to the habbe - habba case. Firstly, the final -e of seko is dropped, while the plural keeps its final -a. But then the expected phonological development is disrupted by the replacement of a plural ending -a with -en, except in the dialect of Schiermonnikoog, where -a is subsequently reduced to -e, just as in the case of habba (§ 2.4.3.4).

The development can be modelled on the same settings as the habbe - habba case, with two differences:

- The sg : pl-ratio for seko is 3:1 (cf. it was 1.4 : 1 for habbe - habba). This ratio is based on the frequency figures from the corpus;
- Because seko has a short root and the final vowels are more prominent, the noise factor of [o] > o and from [a] > [o] is set at 5%, instead of 10%.

Observed and computed figures for <secke> and <seck> as singular forms are given in table 5.18. The algorithm starts in the same year as the habbe - habba case, while the time frame 1430 to 1460 corresponds with run eight (cf. table 5.16). Figures from 1430 to 1460 represent an average year of 1445. Applying the same

---

\[ \text{A comparison of production and perception rates for <secke> as a plural form in the North-East turns out worse. This is due to the low number of relevant tokens. The form <secke> is expected to be infrequent as a plural form between 1430 and 1510. The model produces 17% <secke>. The form <secke> is not attested in the corpus from the North-East. A chi}^2\text{-test on the observed and computed frequencies returns a p-value of 10.3%, which is no reason to reject the null-hypothesis, formulated by the algorithm computation.} \]
time scale as in § 5.2.3, the process would have begun in 1430 = 1445 - (8*2). The first attestation to *seke* without an ending in the North-East is in 1441 (<seeck>, OFO I-83, Tytsjerksteradiel).

The first attestation to *seke* without an ending in the North-East is in 1441 (<seeck>, OFO I-83, Tytsjerksteradiel).

<table>
<thead>
<tr>
<th>Production</th>
<th>&lt;secke&gt;</th>
<th>&lt;seck&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs.</td>
<td>Comp.</td>
<td>Obs.</td>
</tr>
<tr>
<td>1430-1460</td>
<td>56%</td>
<td>64%</td>
</tr>
<tr>
<td>1460-1490</td>
<td>17%</td>
<td>24%</td>
</tr>
<tr>
<td>1490-1510</td>
<td>0%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Table 5.18: Observed (obs.) and computed (comp.) production ratios for <secke> and <seck> as a singular form of the word *seke* 'case'. Correlations > 0.9.

The algorithm predicts a production ratio for <secka> as a plural form of 95% during the time frame 1460 to 1490. In the original charters, the plural is 100% <secka/sacka> until 1490. This shows that developments in the North-East are as expected, based on the *habbe-babba* case, until the late 15th century.

Developments in the south and west

In the south and west of Fryslân, the developments take a different course due to the introduction of the plural marker *-en* (map 2.10). The emergence of this ending *-en* is not a regular case of phonetic noise as implemented in the model. In fact, it is a kind of 'morphological noise' and needs a more extended algorithm to cover this aspect.

The key points on where the south and west differ from the North-East are (compare also table 5.18 and 5.19):

- <secke> is not falling to 0%;
- <secka> is not continuing as a plural and subsequently reducing to <secke> as plural form, but <secka> becomes a variant of the singular form;
- The plural is soon expressed as <secken>.

To model the morphological levelling, the following method is used:

Instead of a constant noise factor from *seka* to *seken*, 1% <secken> is used to begin, to simply introduce the form into the table. The 'phonetic noise' used in the previous computations is replaced by a 'morphological noise'. The morphological noise is the difference between the reliability ratios of <secka> and <secken>. To use an example, in the second run, the reliability ratio of <secken> is 100% and for <secka> this is 97%, causing
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...a morphological noise of 3%. This is fairly low, compared with the default 10% phonetic noise in the model from [a] > [o]. After 22 runs, the difference is 100% - 96% = 4%, etc. This morphological noise is used for the ‘leak’ from <secka> to <secken>, instead of the phonetic noise in the previous case of habbe ~ habba.

Run four of the algorithm matches the first time frame. This puts the beginning of the process at an average year for the first time frame of 1445 minus four runs multiplied by 2 year/run = 1435. This is slightly later than the start of the developments in the north-east. The oldest attestation to <seck> in the south or west is from 1452 (OFO II-217, Boarnsterhim; cf. 1441 for the north-east). The oldest plural form in -en, not as a dative, is from 1447 OFO I-99 (Wünteradiel). This implies that the small difference in timing, suggested by the calibration of the algorithm computations, is not contested by the data from the charters. These settings produce the following computed ratios, which can be compared with observed values in the charters:

<table>
<thead>
<tr>
<th>Production</th>
<th>&lt;secke&gt; as singular</th>
<th>&lt;secke&gt; as plural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs.</td>
<td>Comp.</td>
<td>Obs.</td>
</tr>
<tr>
<td>1430-1460</td>
<td>83%</td>
<td>0%</td>
</tr>
<tr>
<td>1460-1490</td>
<td>26%</td>
<td>9%</td>
</tr>
<tr>
<td>1490-1510</td>
<td>31%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 5.19: Observed and computed production ratios for <secke> as a form of the singular or plural of *seke* ‘case’ in charters from the south and west.

<table>
<thead>
<tr>
<th>Production</th>
<th>&lt;secka&gt; as singular</th>
<th>&lt;secka&gt; as plural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs.</td>
<td>Comp.</td>
<td>Obs.</td>
</tr>
<tr>
<td>1430-1460</td>
<td>4%</td>
<td>83%</td>
</tr>
<tr>
<td>1460-1490</td>
<td>15%</td>
<td>36%</td>
</tr>
<tr>
<td>1490-1510</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 5.20: Observed and computed production ratios for <secka> as a form of the singular and plural of *seke* ‘case’ in charters from the south and west.
The correlations between the observed and predicted data for <secken> as a singular, <secka> as a plural and the plural <secken> are all over 0.9. Data from tables 5.19 to 5.21 is computed from one bidirectional table with one set of input values and parameter settings. The reliability of the procedure should be tested on the total of the model. Combining all the data from the three tables into one correlation test, returns a $r^2 = 0.96$ and a p-value < 0.1%. The cumulative evidence of the results from the algorithm is strong.

The number of singular forms of <secka> is not correctly predicted for the second time frame. In run 63, the model reaches an equilibrium stage, with a level of 3% for <secka>. Therefore the model correctly predicts the existence of <secka> as a possible form of the singular, but at later stages and on a much lower level than observed in the second time frame. Closer evaluation of the base materials reveals that the six tokens of <secka> from the time frame 1460 to 1490, being the 15% in table 5.20, are all from one charter, OFO II-76 (1476) from Wymbritseradiel. Considering the remarks in § 1.3.7.10 (about token count or charter count) the figure of 15% <secka> in the observed data is probably too high.

Therefore, given the existence of the alternative plural ending -en, the algorithm correctly predicts three differences with the North-East:

- <seckce> remains on a fairly high level as a singular in the last time frame (observed 31%, computed 22%) while for the north-east it is observed 0% and computed at 7%;
- The plural preferably becomes -en; a computed 100% -en in the plural is reached in run 37;
- <secka> becomes an optional form of the singular rather than the plural, despite the level and timing of this alternative not always being predicted correctly (or not always being rendered correctly from the scarce data).

The above-mentioned three structural differences between the North-East and the south and west are automatically captured by the algorithm when the introduction of the plural form -en is assumed. It is assumed that a full language simulation
would reveal that this introduction is a consequence of other processes or tensions in the language (a suggestion can be found in § 4.5.2). Where it is due to external, sociological factors such as language contact, it will be more difficult to predict by linguistic modelling.

The conclusion from this section is that the algorithm in the Bidirectional Table has confirmed its ability to make reasonable predictions on the development of different variants under different circumstances. The fact that the model is still useful with a small adjustment in parameter settings, complying with knowledge from § 5.1, generates further support for the concept of linguistic changes as a deterministic process. The interaction of elements is defined by underlying concepts (of articulatory convenience, effective communication and memory formation), while specific parameter settings can be obtained from empirical and phonetic research.

A future challenge is to enhance the model with items such as:

- Priming effect;
- The size of the sample set in the memory from which the ‘common practice’ is computed;
- Replacing probability proportions with statistical variables (cf. Ke 2004, 213 ff.);
- Incorporating different sized speech communities;
- Dynamic categories in the column and row heads.

Section summary:

- The Bidirectional Table model relies on the reductionistic components of ‘articulatory convenience’, ‘common practice’ and ‘effective communication’;
- Shifting ‘grammar’ describing the choice speakers have between different phonological variants, is the result of the interaction of these three components, assuming the language user is a probabilistic learner.