WHAT DICTATES SPELLING?
An OT account of L1 acquisition of Russian vowel reduction

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Abstract

Russian children face a big challenge when it comes to spelling vowels. A significant cause of this difficulty is the phonological phenomenon of vowel reduction. An interesting result of Russian vowel reduction is the merger between /o/ and /a/ in unstressed vowels. This paper uses the BiPhon model (Boersma, 2011), with the addition of an orthographic aspect introduced by Hamann and Colombo (2017), to model the acquisitional process of Russian vowel reduction by L1 speakers. It is found this process can indeed be modelled in BiPhon, by making use of a lexical route, that directly connects underlying form to written form. Specifically, it is found that orthographic constraints on the mapping of (individual) segments, rather than whole-word mapping, suffice for the modelling of this aspect of vowel reduction.

Keywords: Russian, L1 acquisition, vowel reduction, Optimality Theory, BiPhon

1 Introduction

Within the realm of studies into language acquisition, spelling is a relatively understudied topic: it pales in comparison to the number of studies on the acquisition of reading in recent decades, even though studies on English have shown that spelling is complex and requires knowledge of phonology, morphology and orthography (Boulware-Gooden et al., 2015). Systematic studies on spelling in other languages, like Russian, are scarce and rarely written in English (Rakhlin et al., 2017).

Children learning to read and write Russian are faced with a big challenge. The Russian orthography consists of multiple levels: the phonemic level, the syllabic level and the morphemic level. Together, they determine word-stress and, consequentially, the pronunciation of vowels (Rakhlin et al., 2017). This means that a child needs to recognise units on all three levels in a word in order to be able pronounce it, specifically with regards to the unstressed vowels (this will be closer examined in section 2.1) – a system that is considered "unusually complex", typologically speaking (Barnes, 2007, p. 3). This leads to a somewhat paradoxical situation: "It is a bit like the chicken-and-egg problem: you cannot read the word accurately unless you know the stress pattern, but you cannot know the stress pattern unless you read the word" (Kerek & Niemi, 2009, pp. 13–14). Looking at it in the other direction: if a child hears a word pronounced (correctly), the graphic coding (i.e., spelling) of an unstressed vowel in that word cannot be derived.

The goal of this paper is to model the L1 acquisition of spelling unstressed vowels by Russian children. In doing so, this paper aims to test if and how the formal generative model, combining reading and perception, introduced by Hamann and Colombo (2017) – that was originally applied to loanword adaptation – applies to this specific case. Before this account can be formalised, the acquisition of spelling unstressed vowels by Russian-learning children needs to be explored. This will be done in the next section (§2). Then, the generative model by Hamann and Colombo will be presented (§3). Afterwards, the model is applied to Russian unstressed vowels (§4), followed by a discussion (§5).

2 Acquisition of spelling unstressed vowels

This section consists of three parts. In the first part, the relevant part of Russian orthography will be introduced. Then, Russian vowel reduction is explained. This section will also motivate the choice for a demarcation within vowel reduction to apply the model to. The last part will explore various problems for young Russian L1 learners with regards to learning how to spell vowel reduction, specifically within this demarcation.

2.1 Russian vowel orthography

Regarding the vowels, the basic system of Russian consists of five vowels: {i,u,e,o,a}, with positional variants /ɨ/[1] and /ɛ/ (Rakhlin et al., 2017). Orthographically, these seven are all represented with their own grapheme. Additionally, Russian has four graphemes for vowels preceded by a palatal approximant /j/, this includes the grapheme for /e/. In total, this means Russian has ten graphemes that symbolise vowel sounds (Kerek & Niemi, 2009).

The Russian orthographic system can, on the one hand, be seen as transparent and predictable, but on the other hand as complex (Kerek & Niemi, 2009). Whereas Russian has many one-to-one grapheme-to-phoneme mappings, and most graphemes correspond to a limited number of possible phonemes, various sounds could be transcribed with different phonemes (Kerek & Niemi, 2009; Podgaevskaja & Waaijer, 2013). In short, reading (out loud) is relatively easy; spelling is much more difficult (Podgaevskaja & Waaijer, 2013).

An important relevant aspect of Russian orthography for the present study is the marking of word stress, or rather: the lack thereof. Even though word stress is central to the pronunciation of a word (misplaced stress can even lead to a change in word meaning: <плачу́>[2] (*plaču*) ‘pay.1SG.PRS’ versus <пла́чу> (*plaču*) ‘cry.1SG.PRS’), stress is generally not marked orthographically, save for dictionaries and textbooks for beginning learners of Russian (Kerek & Niemi, 2009). To make matters even more complicated for the young learners, stress in Russian is free and mobile, as it can fall on any syllable and can even move under the influence of morphology, e.g., <гора́> (*gora*) ‘mountain’ and <го́ры> (gory) ‘mountains’ (Podgaevskaja & Waaijer, 2013). It is precisely the stress that is one of the most important causes for the discrepancy in transparency between reading and spelling because it results in vowel reduction.

2.2 Russian vowel reduction

Vowel reduction is a process where (typically) an unstressed vowel is not produced as it would be in a stressed position. This is often split into two different types: phonological vowel reduction and phonetic vowel reduction. The former results in languages that have only their full vowel inventory present in stressed syllables, with neutralisations occurring between some of the vowels in unstressed syllables, leaving fewer vowels to be realised in these positions (Barnes, 2007). The latter is a process where vowels in certain positions (most commonly unstressed ones) are produced with phonetic “undershoot”, a process where articulatory

[1] Some include /ɨ/ as a sixth vowel, instead of an allophonic variant of /i/ (Mołczanow, 2015; Rakhlin et al., 2017). This discussion is not relevant for the present study.

[2] Throughout this paper, Cyrillic notation will be presented between <chevrons>, followed by a transliteration in italics into the Latin alphabet between (*parenthesis*), followed by the meaning in English between ‘single quotation marks’. The stress assignment will only be shown in the Cyrillic notation when it is relevant to the example.

gestures are not produced exactly target-like, because of shorter durations of the vowel, resulting in less prototypical realisations of the vowel in question (Lindblom, 1963).

Russian vowel reduction is, as mentioned in the introduction, a prominent topic of study because of its typologically unusual division into two categories, which could be seen as phonological and phonetic (Barnes, 2007). This division, although the nature of the division is a topic of debate beyond the scope of this paper[3], results in different outcomes of the vowel reduction, depending on the position of the vowel. The first occurs in the syllable directly preceding the stressed syllable, often called the *pretonic* syllable. In this position, two mergers occur: the mid vowels /a/ and /o/ merge into the central near-open vowel /ɐ/[4], and the front vowels /i/ and /e/ merge into /i/. The second outcome occurs in the other unstressed, or *atonic*, positions. The only difference between the two is the quality of the merger between /o/ and /a/; it merges into /ə/, in these positions. It must be noted that these processes only occur after "hard" (non-palatalised) consonants. After "soft" (palatalised) consonants, all vowels except /u/ merge into /i/ (Kerek & Niemi, 2009; Rakhlin et al., 2017; Timberlake, 2004). These mergers are consequences of qualitative reduction, i.e., the quality features of a vowel are changed to turn it into a different vowel. This process affects {e,o,a}; the high vowels {i,u} are not affected and remain with the same quality (Barnes, 2007). The Russian vowel reduction also shows quantitative effects, namely in the reduced duration of unstressed vowels (Barnes, 2007).

The process of the merger between /a/ and /o/ after hard consonants is termed *akan'e* 'a-ing (lit.)', as opposed to *okan'e* 'o-ing (lit.)' (Timberlake, 2004). The former is the standard in Contemporary Standard Russian, whereas the latter is only used in some northern dialects (Sussex, 2006). This presence makes the vowel reduction that occurs in unstressed /o/ and /a/ an interesting aspect to model, in addition to the intriguing positional difference between pretonic and atonic occurrence. Thus, akan'e will be the focus of the rest of the paper. The next subsection will already mainly focus on the difficulties arising with the acquisition of the spelling of these vowels.

2.3 Acquisitional difficulties

The spelling of vowels is problematic for Russian children from the start. At the earliest stages, vowels are often either deleted from syllables when they should be present, or added when they should not. An example of the former is <зимй> (*zimj*) instead of <зимой> (*zimoj*)

[3] For a discussion about traditional views and an account of the role of phonetics in phonological theories, see Barnes (2007).
[4] In much literature, this sound is often transcribed as /ʌ/, but the correct IPA symbol should be /ɐ/ (Padgett & Tabain, 2005).

‘in winter’, and an example of the latter is *[5]<театор> (*teator*) instead of <театр> (*teatr*) ‘theater’ (Kuz’mina, 2009, 2011; Pigurnova, 2008;). The deletion of vowels from syllables sometimes even leads to “consonantal writing”, which is assumed to be an effect of the children’s pronunciation while writing, which is often done in early stages of teaching the children how to write (Kuz’mina, 2009; Veličenkova, 2018). An example of a consonantally written word is *<крдл> (*krdl*) instead of <крокодил> (*krokodil*) ‘crocodile’. The children pass this stage relatively quickly, but the problems do not end there. The child is now faced with a complicated choice for the correct grapheme to spell the vowel. There are various types of principles that can determine the spelling of a vowel: traditional, differentiating, phonetic, phonological and morphological (Grigorenko, 2006).

The traditional and differentiating principles govern the spelling of certain words of which the spelling is unintuitive (to an extent) and therefore must be learnt by heart. In the case of traditional spellings, this mostly applies to certain consonant clusters, a clear example of this is the spelling of the word <пожалуйста> (*požalujsta*) ‘please’, which is pronounced /pɐʐałstə/ (Podgaevskaja & Waaijer, 2013). The differentiating principle applies more rarely: it is simply a means to differentiate between two different words that would otherwise be undistinguishable because they are pronounced the same. Intuition will, in these cases, leave one with (at least) two spelling options, so these words also need to be learnt by heart. An example is <ожог> (*ožog*) ‘a burn’ versus <ожёг> (*ožjog*) ‘burn.3SG.M.PST’ (Grigorenko, 2006).

The phonetic principle is the most transparent one, and the easiest principle to follow for the young learners (Podgaevskaja & Waaijer, 2013). This principle applies when a word is spelled the way it sounds. Regarding akan’e, this means that unstressed vowels (especially pretonic ones, as they sound even closer to /a/ than in atonic position) are spelled as <a> – which we know is not always correct. A spelling of *<малакó> (malako) instead of <молокó> (moloko) ‘milk’ is indicative of this principle. These spelling mistakes are indeed observed to be the most common ones in a case study on 8-year-old Russian children (Sal’nikova, 2013). Contrastively, Kharchenko (2013) finds that children also engage in some form of hyper-correction, where the child hears something close to /a/ and knows that that sound is often written as <o>, so it will (incorrectly) write <o>, when it should have been <a>. An example is the spelling *<шога> (šoga) when confronted with the input of /ʂɐˈga/, when the correct spelling was <шага> (šaga) ‘steps’. These two opposing observations show how hard the choice

[5] The asterisk is used to indicate an incorrect spelling.

between the two graphemes is for children. While harder to learn, the phonological and morphological principles can provide some assistance.

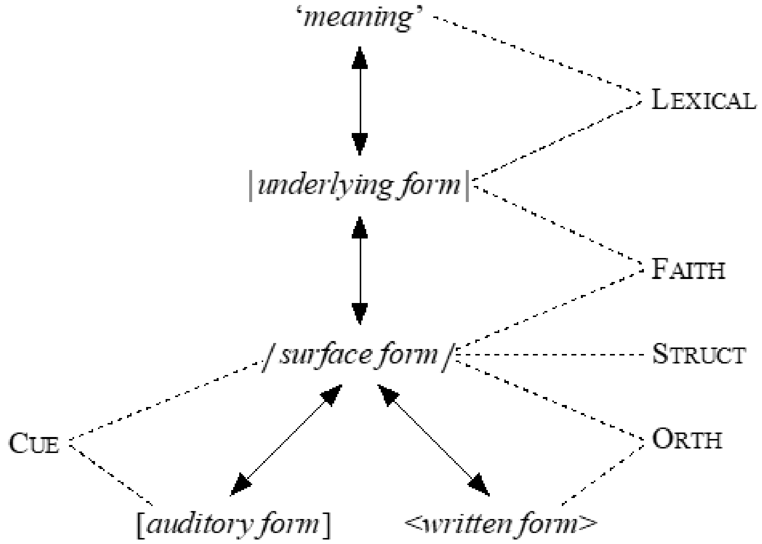
According to both of these principles, morphemes and stems must always be spelled in the same way, regardless of their position in a word or the surrounding segments, even if the pronunciation is different in some cases (Podgaevskaja & Waaijer, 2013). For the cases relevant to akan’e, this means that it applies to the example from section 2.1: <гора́> and <го́ры>. Even though the <о> is unstressed in the former word and sounds different to the stressed one in the latter, it should still be spelled the same. Morphologically, for example, a preposition containing an <о>, e.g., <по> (*po*) ‘on (i.a.)’, should always be spelled as such, even when it becomes unstressed in front of a noun or as prefix of a verb. This means that children must first learn the relationships between words like <гора́> and <го́ры> in order to properly apply these principles (Grigorenko, 2003). An important consequence of connecting these words is that the children identify the vowels in a stem in strong (stressed) and weak (unstressed) positions, especially considering the mobility of word stress (Grigorenko, 2003; Kerek & Niemi, 2009).

It is not unexpected, then, that children are found to acquire stress assignment earlier than vowel reduction, likely because children are already sensitive to prosodic patterns in early childhood (Podgaevskaja & Waaijer, 2013). From a logical standpoint, it also makes sense that children can only start to acquire vowel reduction when they realise which vowel is stressed and which vowels are unstressed – and, thus, subjected to the reduction process. This stage, where children have acquired stress assignment, will be the starting point of the analysis (§4). Before that, the next section (§3) will introduce the model used for this analysis.

3 The BiPhon model

The bidirectional phonology and phonetics (BiPhon) model is a grammar model that is capable of modelling acquisition and evolution of language (Boersma, 2007, 2011). Using this model as a basis, Apoussidou (2007) added an extra *meaning* layer. Later, Hamann and Colombo (2017) added an orthographic component. The model, as taken from the latter authors, is shown in Figure 1.

Figure 1: The BiPhon model (Boersma, 2007, 2011) with a meaning component (Apoussidou, 2007) and an orthographic component (Hamann & Colombo, 2017).



This formal model makes use of Optimality Theory (OT), which was introduced by Prince and Smolensky (1993 [2004]). In OT, different *forms* – representations of words – are related to each other. The relation, or *mapping*, between forms is regulated by *constraints*. The constraints are rules of sorts that evaluate the mapping between two forms (or, sometimes, a form on its own). Crucial to this model, the constraints work in two ways, hence the name "bidirectional" and the double arrows in the figure. Practically, this means that either of the two forms can be regarded as the input form (and any of the two forms as output form). The input form is then subjected to all the constraints in order to get to the most optimal of all possible outputs, which are often referred to as "candidate" outputs (Prince & Smolensky, 1993 [2004]). The relative *ranking* of the various constraints is what ultimately decides the winning candidate, as we will see later in the analysis. Going from the bottom to the top, the BiPhon model simulates comprehension; in the other direction, it models production. In the next subsections (§3.1 through §3.4), the model will be explained in parts. In each subsection, one of the mappings between forms will be featured along with their relevant constraints.

3.1 Semantic mapping

We start at the top of the model: the mapping between meaning and |*underlying form*| (UF, notated between vertical lines). This mapping could be referred to as semantic mapping. In the terms first introduced by De Saussure (1916), this is the pairing of the signifier (in this model, the UF) and the signified (the meaning). That means that the UF is some sort of mental representation of a word, that contains phonological material (Boersma, 2011). The semantic mapping is evaluated through LEXICAL constraints. In the BiPhon model, one general LEXICAL constraint is introduced, slightly rephrased in (1) (Boersma, 2011, p. 57).

(1) *‘ ’[6]|*x*|: Assign a violation for every non-word that is mapped onto an underlying form, and vice versa.

This constraint prohibits any UF to be a non-word, and vice versa. If it is ranked very high, that means every UF has to be mapped onto an (existing) morpheme in a language.

3.2 Phonological mapping

Mapped onto the UF is the /*surface form*/ (SF, notated between solidi). This is a phonological form that contains information about many phonological elements like syllable structure. Because languages can have restrictions on certain phonological sequences, e.g., consonant clusters, the SF form is evaluated by STRUCT(URAL) constraints. These are constraints about the phonotactics of a language, that could prohibit, for example, these consonant clusters. Since the SF is restricted by STRUCT constraints, it may diverge from the UF (which is not restricted by those constraints). However, in order to limit this divergence, FAITH(FULNESS) constraints evaluate the mapping between the SF and the UF. These constraints are violated when a segment in one of the forms is not identical to the corresponding segment in the other form. A general STRUCT constraint is shown in (2a) and two general FAITH constraints are shown in (2b-c).

(2) a. */*P*/: Assign a violation for every surface form /*P*/.

b. IDENT F_{US}[7]: Assign a violation for every underlying segment that does not have the feature *F* mapped onto the corresponding surface form, and vice versa.

c. |*x*|/*P*/: Assign a violation for every underlying form |*x*| that is not mapped onto the surface form /*P*/, and vice versa.

3.3 Phonetic mapping

Descending in the model, we arrive at the mapping from the SF onto an [*auditory form*] (AF, notated between square brackets). This is the bridge between the phonological form and the phonetic form, which could be considered phonetic[8] mapping. Here, an SF segment is mapped onto an auditory cue, for example frequency (in Hertz) or duration (in ms). Predictably,

[6] The empty space between the quotation marks indicates that there is no meaning, i.e., it is a non-word. Oppositely, in the case of a real word, this would have contained the meaning, like ‘mountain’ (from §2.1).

[7] Following the conventions by Boersma (2011), the subscript S (and U) refer to surface (form) and underlying (form), meaning that this constraint evaluate the forms specified in the subscript. For example, constraint (10a) only evaluates the surface form, whereas constraints (10b,c) evaluate the combination of the two forms.

[8] Boersma (2011) calls this prelexical comprehension, rather than phonetic, as he includes another layer beneath the AF: the articulatory form. The process of going from SF to the articulatory form he calls phonetic production/comprehension. Because this extra layer is not included in the present model, phonetic mapping is used as a term here, since it is a more graspable term.

this involves CUE constrains. A general cue constraint is provided in (3), adapted from Boersma (2011, p. 48).

(3) /*P*/ [*F1 = x Hz*]: Assign a violation for every surface form /*P*/ that is not mapped onto an auditory form with an F1 of *x* Hz, and vice versa.

It is important to note that this adaptation is a simplification for clarity. Boersma (2011, p. 48) formulates the general CUE constraint of */*P*/ [*F1 = x Hz*], due to the exclusive nature of OT constraints. This means that a surface form /*P*/ has many constraints, namely for mappings on every possible auditory form. As shown by Escudero and Boersma (2003, 2004), the ranking of these constraints relative to each other indicates what the most prototypical frequency in Hertz is for a surface form. The constraint with the mapping onto that prototypical frequency is ranked the lowest, and as to the constraints on the other mappings: the further away the frequency from the prototypical one, the higher the constraint on this mapping is ranked. The constraint in (3) is a reversely phrased one, that incorporates all the negatively formulated constraints, by prohibiting any form that is not the prototypical one. In section 4.1, this will be exemplified.

3.4 Orthographic mapping

Finally, there is the orthographic mapping between an SF and a <*written form*> (WF, notated between chevrons). These mappings are formalised through ORTH(OGRAPHIC) constraints. Some general constraints are listed in (4), taken from Hamann and Colombo (2017, p. 690).

(4) a. <γ>/*P*/: Assign a violation mark to every grapheme <γ> that is not mapped onto the phonological form /*P*/ and vice versa.

b. *<γ>/ /: Assign a violation mark to every grapheme <γ> that is mapped onto an empty segment in the SF.

c. *< >/*P*/: Assign a violation mark if the absence of a grapheme is mapped onto the phonological form /*P*/.

These last two constraints form the orthographic principle proposed by Wiese (2004), that one letter should correspond to one sound.

While this orthographic mapping connects the WF to the SF, there is another possibility. Hamann & Colombo’s (2017) model (from Figure 1) makes use of the so-called *sub-lexical* route. As we have seen, this route makes use of a phonological form (the SF) to interpret and produce auditory and written forms. As is visualised in the model, this form operates “below” the lexical level, meaning that there is no lexical influence on the SF. Hence, this route is sub-lexical. However, the authors also provide a different route that bypasses the SF. They call this the *lexical route*. Both routes are based on the *dual-route* (DR) *model* by Coltheart and colleagues (1993 [2013], 2001). In the DR model, both the lexical and the sub-lexical route are in competition when reading words (Hamann & Colombo (2017). Hamann and Colombo argue that, in the bypassing of the SF, the UF (connected to a meaning) and WF are directly linked through whole-word mappings. This is necessary in the case of heterographs – words that are written differently but pronounced the same, e.g., English <son> and <sun>. These WFs are then linked to their respective UFs, instead of their (identical) SFs. However, Hamann and Colombo (2017, p. 703) also suggest that a different type of mapping could be possible in some cases: using ORTH constraints on single segments, similar to the ones between SF and WF. As section 4.4.2 will prove, the mapping of single segments suffices for the case at hand. A general constraint is shown in (5).

(5) |*x*|<γ>: Assign a violation for every underlying form |*x*| that is not mapped onto the grapheme <γ>, and vice versa.

4 Modelling the acquisition of vowel reduction

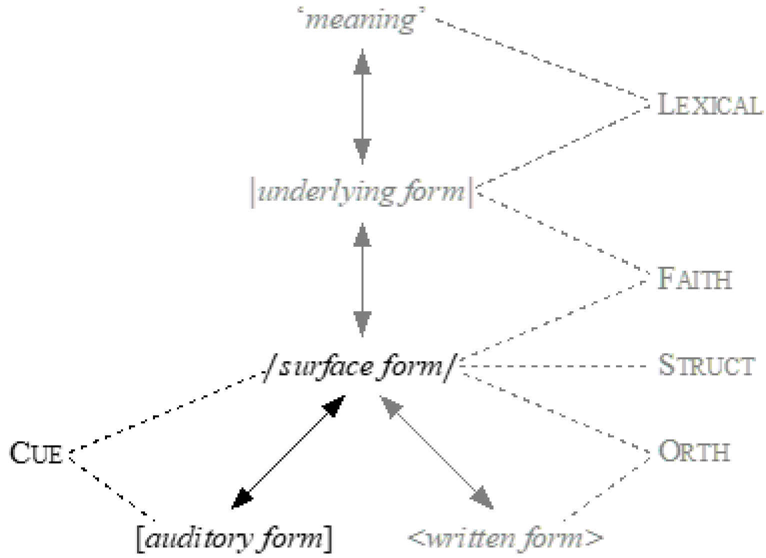
This section contains the modelling of the acquisition process of vowel reduction by the Russian L1 learners. The next four sections will take us through this process, one level of mapping at a time. The order of these sections/mappings is chronological, i.e., following what is thought to be the steps of a learner. First, the phonetic mapping will be discussed (§4.1); then the phonological mapping, with some attention to STRUCT constraints (§4.2); afterwards, the semantic mapping (§4.3); and lastly, the orthographic mapping (§4.4).

It is important to mention again that the starting point of this analysis is when the children have acquired word stress, as it is a requirement for learning vowel reduction. As mentioned in section 2.3, this is indeed a stage that children arrive at – being sensitive to word stress, but not able to apply vowel reduction. A final remark is that the process will be illustrated through the word <стол> (*stol*) 'table', and its inflected form <столá> (*stola*) 'table (genitive)', to provide some consistency when going through the various (complex) stages of the model.

4.1 Phonetic mapping

Learning Russian – or any language, for that matter – starts with auditory input: the children cannot yet read, nor have some form of omniscient lexical knowledge. Therefore, it is assumed that children start building their mental lexicon through auditory input, which happens in the phonetic mapping of the AF to the SF – the highlighted part of the model in Figure 2.

Figure 2: Phonetic mapping as part of the BiPhon model.



The auditory input in this case consists of the four vowels are relevant to this study, mentioned in section 2.2: {o,ə,ɐ,a}, which occur after non-palatalised consonants. These vowels require different tongue placement and mouth shape (Jones & Ward, 2011). Acoustically, the placement and shape are most clearly reflected in the frequency of the first and the second formant (F1, F2), which are resonance frequencies picked up by the basilar membrane in human ears, expressed in Hertz (Boersma, 2014). In terms of F1 and F2, the following values can be given to the vowels in question (Table 1), based on data from Barnes (2007, p. 11) and Padgett and Tabain (2005, p. 29).

Table 1: Average formant frequencies of auditory {o,ə,ɐ,a} (occurring after non-palatalised consonants).

Vowel	Formant 1 value in Hz	Formant 2 value in Hz
o	500 Hz	1100 Hz
ə (atonic position)	600 Hz	1450 Hz
ɐ (pretonic position)	700 Hz	1450 Hz
a	750 Hz	1500 Hz

To distinguish these sounds, speakers need CUE constraints. It seems that F1 frequency is the best characteristic to distinguish these sounds, which is also found by Barnes (2007) and Padgett and Tabain (2005). The boundaries between the categories of the vowels based on their F1 can thus be taken as the basis of the CUE constraints in (6). As mentioned in section 3.3, these constraints are simplifications of many negatively formulated constraints, prohibiting mappings onto all other possible frequencies. For example, (6a) stands for many constraints such as *[F1 = 500 Hz]/o/, *[F1 = 600 Hz]/o/, *[F1 = 700 Hz]/o/, *[F1 = 800 Hz]/o/, which are ranked low to high (the higher the frequency, the further away it is from the prototypical 500 Hz, thus the higher ranking). Since the constraints in (6) relate to different frequencies and vowels due to their rephrasing, they are not in competition, so their relative ranking is not of influence. Therefore, they will be ranked equally high, reflected in the OT tableaus (Tableau 1 and 2) by the dotted lines (as opposed to solid lines) between the constraints.

(6) a. [F1<550 Hz]/o/: Assign a violation mark to every auditory form with a first formant value lower than 550 Hz that is not mapped onto the surface vowel /o/, and vice versa.

b. [F1=550-650 Hz]/ə/: Assign a violation mark to every auditory form with a first formant value between 550 Hz and 650 Hz that is not mapped onto the surface vowel /ə/, and vice versa.

c. [F1=651-725 Hz]/ɐ/: Assign a violation mark to every auditory form with a first formant value between 651 Hz and 725 Hz that is not mapped onto the surface vowel /ɐ/, and vice versa.

d. [F1>725 Hz]/a/: Assign a violation mark to every auditory form with a first formant value higher than 725 Hz that is not mapped onto the surface vowel /o/, and vice versa.

These constraints help the child decide what it hears in the auditory input, by distinguishing the various vowels from one another. But this is not the only auditory cue that the child receives. As mentioned, the children in question are able to hear whether a syllable is stressed, as it is a requirement for acquiring vowel reduction. This information is said to be conveyed through many different cues, such as duration (Barnes, 2007; Padgett & Tabain, 2005; Mołczanow, 2015) and tone (Mołczanow, 2015). Because the nature of the stress is not relevant to this paper, all potential cues are summarised in the following CUE constraint (7).

(7) [STRESSED]/ˈV/: Assign a violation mark to every stressed auditory form that is not mapped onto a stressed phonological form, and vice versa.

The constraint is ranked the highest in order to correctly illustrate that the child has the knowledge of where the stress lies. The working of the constraints in (6-7) is shown in Tableau 1, where the input is an auditory form that has a stressed vowel with an F1 of 510 Hz. In this tableau, we can see that the candidate /stoł/ (i.e., the Russian word <стол> (*stol*) ‘table’) is selected from the input (“☜” marks the winning candidate in the comprehension direction), as the vowel in the input has a frequency of lower than 550 Hz, ruling out all the other candidates. The first constraint does not lead to a fatal violation for any candidate, as the input consisted of one vowel, which then can only be stressed.

Tableau 1: Auditory [st V$_{\text{[STRESSED, F1 = 510 Hz]}}$ ɫ] to surface /stoɫ/.

[stV$_{\text{[STRESSED, F1 = 510 Hz]}}$ ɫ]	[STRESSED] /ˈV/	[F1<550 Hz] /o/	[F1=550-650 Hz] /ə/	[F1=651-725 Hz] /ɐ/	[F1>725 Hz] /a/
☜ a. /stoɫ/					
b. /stəɫ/		*!	*		
c. /stɐɫ/		*!		*	
d. /staɫ/		*!			*

Tableau 2 shows an auditory input with two vowels (an unstressed vowel with an F1 of 699 Hz and a stressed vowel with an F1 of 765 Hz), namely that corresponding to /stɐ.ˈɫa/ (i.e., the word <столá> (*stola*) 'table (genitive)'), where this first constraint does play an important role in the selection. As can be seen in the tableau, the candidates with the stress on a different syllable than in the input, are directly eliminated.

Tableau 2: Auditory [st V$_{\text{[F1 = 699 Hz]}}$ ɫ V$_{\text{[STRESSED, F1 = 765 Hz]}}$] to surface /stɐ.ˈɫa/.

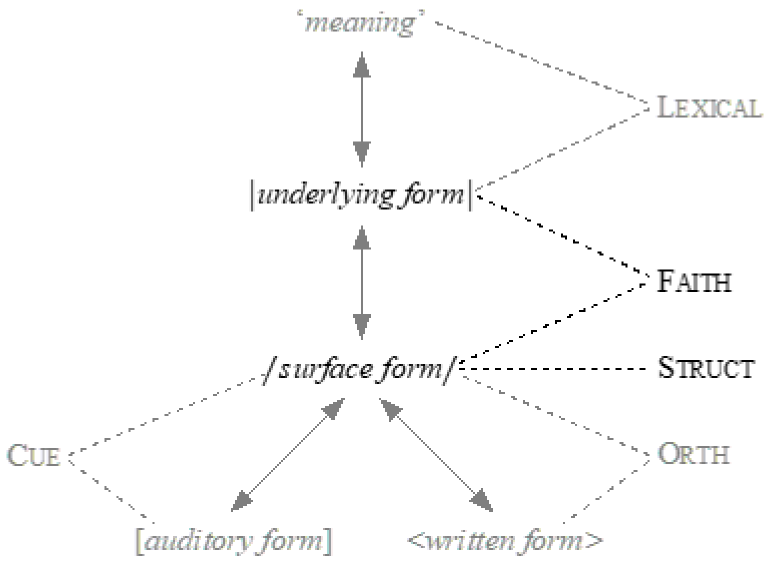
[stV$_{\text{[F1 = 699 Hz]}}$ ɫV$_{\text{[STRESSED, F1 = 765 Hz]}}$]	[STRESSED] /ˈV/	[F1<550 Hz] /o/	[F1=550-650 Hz] /ə/	[F1=651-725 Hz] /ɐ/	[F1>725 Hz] /a/
a. /sto.ˈɫa/		*!		*	
b. /ˈsto.ɫa/	*!	*		*	
c. /stə.ˈɫa/			*!	*	
d. /ˈstə.ɫa/	*!		*	*	
☜ e. /stɐ.ˈɫa/					
f. /ˈstɐ.ɫa/	*!				
g. /sta.ˈɫa/				*!	*
h. /ˈsta.ɫa/	*!			*	*

Through the phonetic mapping, the SF is determined on the basis of the AF. As we have seen in this section, this leads to a situation where the two AFs have two different SFs, even though they share the same stem. Their UF should reflect this correspondence, which brings us to the next step for our word: the phonological mapping.

4.2 Phonological mapping

This section will be divided into two subsections, the phonological mapping before vowel reduction is acquired (§4.2.1) and the one with vowel reduction (§4.2.2). As mentioned in section 3.2, the phonological mapping happens between the UF and the SF. In the early stages of language learning, the child has to process the SF (coming from their auditory input) in order to save it in their mental lexicon. In the BiPhon model, this is done through the UF. This process is highlighted in Figure 3.

Figure 3: Phonological mapping as part of the BiPhon model.



4.2.1 Lexicon optimisation

It is assumed that children in early stages of L1 learning map the information from the SF as faithful as possible to the UF (Boersma & Levelt, 2004), a process which is coined as “lexicon optimisation” by Prince and Smolensky (1993 [2004]). The mapping of the respective vowels from SF to UF is thus formed by the FAITH constraints in (8). Like the ones in (6), these constraints have the same rank, since they involve different UFs and SFs, and are, thus, not in competition with one another. This means that in the situation that, for example, candidate X violates (8a), and candidate Y violates (8b), this is considered a “tie”, and neither violation will be fatal. This feature will prove to be crucial at a later stage in the process.

(8) a. |o|/o/: Assign a violation mark to every underlying vowel |o| that is not mapped onto the surface form /o/, and vice versa.

b. |ə|/ə/: Assign a violation mark to every underlying vowel |ə| that is not mapped onto the surface form /ə/, and vice versa.

c. |ɐ|/ɐ/: Assign a violation mark to every underlying vowel |ɐ| that is not mapped onto the surface form /ɐ/, and vice versa.

d. |a|/a/: Assign a violation mark to every underlying vowel |a| that is not mapped onto the surface form /a/, and vice versa.

This means that the SFs from Tableau 1 and 2 are saved separately as |stoł| and |stɐˈła|. The child does not yet know that these forms are related, and that, crucially, the surface vowel /ɐ/ is actually an allophone of the underlying vowel |o|. This realisation lays the foundation for learning vowel reduction.

4.2.2 Vowel reduction

Vowel reduction causes a discrepancy between corresponding segments in UF and SF. For children to learn this, they need to be successful in connecting related forms, as stated by Grigorenko (2003), such as /stoł/ and /stɐ.ˈła/ from section 4.1, which were saved separately at the end of the lexicon optimisation stage (§4.2.1).

To model the reduction process of our relevant vowels, the introduction of new constraints becomes necessary. First, however, the concept of sonority needs to be introduced, as it plays a crucial role in the foundation of the process of vowel reduction. Sonority as a feature is the topic of much debate[9]. Because this paper is concerned only with the application of the feature of sonority, it will suffice to say that sonority has to do with the (lack of) restriction in the airways when producing sounds. Very concisely, this means that segments (in this case: vowels) that are produced more open and peripherally, are more sonorous. Consequentially, they can be put into a hierarchical order. The order, as listed by De Lacy (2006, p. 68), was applied to Russian vowels by Mołczanow (2015, p. 110), and is shown in (9), going from the least sonorous (i) to the most sonorous (vii).

(9)
i. high central vowels {ɨ}
ii. mid central vowels {ə}
iii[10]. (near-)low central vowels {ɐ}
iv. high peripheral vowels {i,u}
v. mid-high peripheral vowels {e,o}
vi. mid-low peripheral vowels {ɛ,ɔ}
vii. low peripheral vowels {a}

---

9 See Parker (2002) for a comprehensive discussion on the topic.

10 This category was not included in the hierarchies by De Lacy (2006) and Mołczanow (2015), but is included in this paper for completeness and further application of this hierarchy. The International Phonetics Association (1999) classifies it as a near-open (or near-low) central vowel, whereas others, like Padgett and Tabain (2005, p. 16) describe it as mid-low. It is added as a (near-)low central vowel because the feature [+low] is crucial to the present analysis.

According to De Lacy (2006), vowel reduction stems from a preference to lower the sonority in vowels that are unstressed. Mołczanow (2015, p. 116) applies this view to Russian vowel reduction, by constructing a STRUCT constraint that requires unstressed vowels to have a sonority lower than {i,u}, but since this cut-off point is arbitrary, and because the present analysis makes use of an extra category (9iii), this constraint is altered to also assign less or more severe violations based on the sonority of the concerned vowel (see 10a). Naturally, if the preference is to lower the sonority as much as possible, this would always result in reduction towards /ɨ/, which is the Russian phoneme with the lowest sonority. As we know from section 2.2, the reduction instead results in /ə/. The reason for this, according to Mołczanow (2015), are some faithfulness constraints that require the SF to be as faithful as possible to the UF with regards to the features of the vowel. The high central vowel /ɨ/ does not share the feature [-high] with the UFs |o| and |a| because it is [+high]. The FAITH constraint (Mołczanow, 2015, p. 120) formalised in (10b) thus prevents this mapping. Crucially, following the reasoning of Van Oostendorp (1995) that /ə/ is underspecified for these features, it cannot be unfaithful to this (or any other) feature constraint. Russian, thus, ends up with a reduction towards /ə/, which is conform the TETU (The Emergence of The Unmarked) effect, proposed by McCarthy and Prince (1994), as it is the most unmarked segment. Since the vowels under the main stress of the word are not reduced, they need to be excluded from this process. This can be done by a high-ranked FAITH constraint preventing deviation between the UF and SF of a stressed vowel (10c), reformulated from Mołczanow (2015, p. 120).

(10) a. $*^{/>}V_{[sonority]S}$: Assign a violation to every unstressed vowel per step that the vowel is away from {ɨ} (see (9)).

b. IDENT $V_{[-high]US}$: Assign a violation for every unstressed underlying vowel that does not have the feature value [-high] mapped onto the corresponding surface form, and vice versa.

c. IDENT $'V_{US}$: Assign a violation for every stressed underlying vowel that is not mapped onto an identical surface form, and vice versa.

To show the working of the constraints, the SF is generated from the UF for our word <стола́> (Tableau 3), but also for the word <ко́шка> (*koška*) 'cat' (Tableau 4), to show that the same process works similarly for two different unstressed vowels, as well as different positions relative to the stress[11]. The winning candidates are marked with "☞" this time, to illustrate that this is the production direction.

Tableau 3: Underlying |stoˈɫa| to surface /stə.ˈɫa/.

|stoˈɫa|	IDENT ˈV_{US}	IDENT $V_{[-high]US}$	$*^{/>}V_{[sonority]S}$	|o| /o/	|ə| /ə/	|ɐ| /ɐ/	|a| /a/
a. /sto.ˈɫa/			**!**				
b. /stɨ.ˈɫa/		*!		*			
☞ 💣 c. /stə.ˈɫa/			*	*	*		
d. /sti.ˈɫa/		*!	***	*			
e. /stɐ.ˈɫa/			**!	*		*	
f. /sta.ˈɫa/			**!****				
g. /sto.ˈɫə/	*!		****				*
h. /stə.ˈɫə/	*!		*	*	**		*

Tableau 4: Underlying |ˈkoʂka| to surface /ˈkoʂ.kə/.

|ˈkoʂka|	IDENT ˈV_{US}	IDENT $V_{[-high]US}$	$*^{/>}V_{[sonority]S}$	|o| /o/	|ə| /ə/	|ɐ| /ɐ/	|a| /a/
a. /ˈkoʂ.ka/			**!****				
b. /ˈkoʂ.kɨ/		*!					*
☞ c. /ˈkoʂ.kə/			*		*		*
d. /ˈkoʂ.ki/		*!	***				*
e. /ˈkoʂ.kɐ/			*!*			*	*
f. /ˈkəʂ.ka/	*!		*******	*	*		
g. /ˈkəʂ.kə/	*!		*	*	**		*

These tableaus are, as expected, extremely similar to each other, regardless of the different structure of their input. But there still is one missing link. As explained in section 2.2, the Russian vowel reduction has two levels. The constraints in (10) only take care of the strong (atonic) reduction. However, as we know from section 2.2, the pretonic reduction is less strong. Because this only applies to words that have a pretonic syllable, like <столá>, which means that only the outcome from Tableau 3 is incorrect (which is indicated by a bomb symbol (💣)). To differentiate between pretonic stress and atonic stress, another STRUCT constraint is necessary (11).

[11] Since we have established that the children are aware of the correct stress placement, only candidates with the same stress placement will be considered.

(11) $V'_{[+low]S}$: Assign a violation for every pretonic surface vowel that does not have the feature value [+low] mapped onto the surface form.

When this constraint is ranked above the one from (10a) – preferring lower sonority levels, the vowel /ɐ/ will be preferred over /ə/, since the latter does not have the feature [+low]. Effectively, this leads to a more sonorous pretonic vowel than any atonic vowel. This has been accounted for in different ways. Some researchers argue for a metrical system of iambic feet, where the unstressed syllable of the main feet attracts more sonorous segments, see, for example, Crosswhite (2001), but there are also arguments in favour of trochaic feet (see Mołczanow (2015) for a discussion on this). Mołczanow herself argues for the role of tone, where a high tone of the stressed syllable spreads left to the preceding vowel, thus facilitating a more sonorous segment. Since this paper does not concern itself with the (potentially) metrical technicalities that cause the difference between atonic and pretonic stress, but rather with the process of acquiring the correct realisation, the constraint in (11) is only formalised to ensure a correct application. It does not elicit a violation in the /ə/ in /ˈkoʂ.kə/ because, in that context, the vowel is not pretonic. The effect of the constraint is shown in Tableau 5, which the same as Tableau 3, but with the addition of (11).

Tableau 5: Underlying |stoˈɫa| to surface /stɐ.ˈɫa/ (Tableau 3 expanded).

<table>
<tr><th>|stoˈɫa|</th><th>IDENT ˈV_{US}</th><th>IDENT V[-high]_{US}</th><th>Vˈ[+low]_S</th><th>*/>V[sonority]_S</th><th>|o|
/o/</th><th>|ə|
/ə/</th><th>|ɐ|
/ɐ/</th><th>|a|
/a/</th></tr>
<tr><td>a. /sto.ˈɫa/</td><td></td><td></td><td>*!</td><td>****</td><td></td><td></td><td></td><td></td></tr>
<tr><td>b. /stɨ.ˈɫa/</td><td></td><td>*!</td><td>*</td><td></td><td>*</td><td></td><td></td><td></td></tr>
<tr><td>c. /stə.ˈɫa/</td><td></td><td></td><td>*!</td><td>*</td><td>*</td><td>*</td><td></td><td></td></tr>
<tr><td>d. /sti.ˈɫa/</td><td></td><td>*!</td><td>*</td><td>***</td><td>*</td><td></td><td></td><td></td></tr>
<tr><td>☞ e. /stɐ.ˈɫa/</td><td></td><td></td><td></td><td>**</td><td>*</td><td></td><td>*</td><td></td></tr>
<tr><td>f. /sta.ˈɫa/</td><td></td><td></td><td></td><td>***!***</td><td>*</td><td></td><td></td><td>*</td></tr>
<tr><td>g. /sto.ˈɫə/</td><td>*!</td><td></td><td>*</td><td>****</td><td></td><td></td><td></td><td>*</td></tr>
<tr><td>h. /stə.ˈɫə/</td><td>*!</td><td></td><td>*</td><td>*</td><td>*</td><td>**</td><td></td><td>*</td></tr>
</table>

With these constraints, every underlying |o| and |a| will be turned into a surface /ə/ in atonic position, and into a surface /ɐ/ in pretonic position. So, the production direction – from UF to SF – is not problematic. Because of the bidirectionality of the model, we can add the comprehension to the tableau. This is done by putting all UF-SF pairs that share at least one of the representations from Tableau 5 as candidates. The outcome is a tableau that shows a winner for the production direction (☞) and for the comprehension direction (☜). Tableau 6 shows that there are two different winners: the production direction provides the correct winner, the comprehension direction does not, as indicated by the bomb symbol.

Tableau 6: UF-SF pairs of |stoˈła| /stɐ.ˈła/, showing different production and comprehension winners.

<table>
<tr><th>|stoˈła| /stɐ.ˈła/</th><th>IDENT ˈV_{US}</th><th>IDENT $V_{[-high]US}$</th><th>$Vˈ_{[+low]S}$</th><th>$*^{/>}V_{[sonority]S}$</th><th>|o| /o/</th><th>|ə| /ə/</th><th>|ɐ| /ɐ/</th><th>|a| /a/</th></tr>
<tr><td>a. |stoˈła| /sto.ˈła/</td><td></td><td></td><td>*!</td><td>****</td><td></td><td></td><td></td><td></td></tr>
<tr><td>b. |stoˈła| /stə.ˈła/</td><td></td><td></td><td>*!</td><td>*</td><td>*</td><td>*</td><td></td><td></td></tr>
<tr><td>☞ c. |stoˈła| /stɐ.ˈła/</td><td></td><td></td><td></td><td>**</td><td>*!</td><td></td><td>*</td><td></td></tr>
<tr><td>d. |stoˈła| /sta.ˈła/</td><td></td><td></td><td></td><td>***!***</td><td>*</td><td></td><td></td><td>*</td></tr>
<tr><td>e. |stəˈła| /stɐ.ˈła/</td><td></td><td></td><td></td><td>**</td><td></td><td>*!</td><td></td><td>*</td></tr>
<tr><td>💣 ☜ f. |stɐˈła| /stɐ.ˈła/</td><td></td><td></td><td></td><td>**</td><td></td><td></td><td></td><td></td></tr>
<tr><td>g. |staˈła| /stɐ.ˈła/</td><td></td><td></td><td></td><td>**</td><td></td><td></td><td>*!</td><td>*</td></tr>
</table>

What has not been incorporated into the tableau, however, is the assumption that a child learns over time which form should be taken as underlying. This could be explained by the Gradual Learning Algorithm (GLA), which states that the composition of various input forms, but also the child's ability to notice the mismatches between what they may expect to hear [stɐł] and what they do hear [stoł], leads to the favouring of the most common/correct UF (Boersma & Levelt, 2004). Within the OT framework, this is regarded a process of reranking of constraints, where specific previously low-ranked constraints are gradually moving up in the ranking, for example through more exposure of certain forms in the input (Boersma & Hayes, 2001; Boersma & Levelt, 2004). When these constraints start outranking other constraints that were previously decisive in the selection process, the winning candidate could change. In this case, this means that a child will learn that /ə/ and /ɐ/ cannot be mapped on identical UFs. In other words, |ə| and |ɐ| cannot be valid UFs. This means that any constraints prohibiting |ə| and |ɐ|, during the learning process, end up being ranked above the FAITH constraints from (8b-c), whereas, before the learning process, they were ranked below them. In totality, these new higher-ranked constraints are the following: *|ə|/o/, *|ə|/ə/, *|ə|/ɐ/, *|ə|/a/, *|ɐ|/o/, *|ɐ|/ə/, *|ɐ|/ɐ/, *|ɐ|/a/, namely all possible mappings with one of the central vowels as UF. To prevent the tableaus from getting too long, these constraints are summarised in (12), seemingly contrary to conventions (which state that FAITH constraints must include a mapping between a UF and an SF). The description, however, does reflect this mapping. It also has to be noted that, relative to each other, (12a) and (12b) are ranked equally, like the constraints from (6) and (8).

(12) a. *|ə|: Assign a violation mark to any mapping between an underlying |ə| and a surface {o,ə,ɐ,a}, and vice versa.

b. *|ɐ|: Assign a violation mark to any mapping between an underlying |ɐ| and a surface {o,ə,ɐ,a}, and vice versa.

In Tableau 7, we see these constraints in action, where they are ranked above their respective counterparts. For clarity, the first two constraints (IDENT ˈV$_{US}$ and IDENT V$_{[-high]US}$) from Tableau 6 have been excluded, since they did not cause any fatal violations among the candidates, and are, thus, not decisive in selecting the winning candidate in this case.

Tableau 7: UF-SF pairs of |stoˈła| /stɐ.ˈła/, showing identical production and comprehension winners.

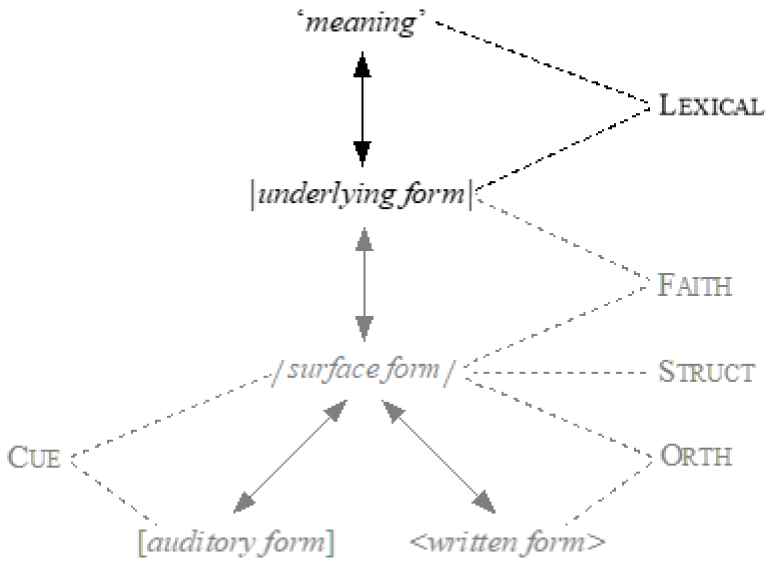
|stoˈła| /stɐ.ˈła/	Vˈ$_{[+low]S}$	$*^{/>}V_{[sonority]S}$	*|ə|	*|ɐ|	|o| /o/	|ə| /ə/	|ɐ| /ɐ/	|a| /a/
a. |stoˈła| /sto.ˈła/	*!	****						
b. |stoˈła| /stə.ˈła/	*!	*			*	*		
☜ ☞ c. |stoˈła| /stɐ.ˈła/		**			*		*	
d. |stoˈła| /sta.ˈła/		***!***			*			*
e. |stəˈła| /stɐ.ˈła/		**	*!			*		*
f. |stɐˈła| /stɐ.ˈła/		**		*!				
💣 ☜ g. |staˈła| /stɐ.ˈła/		**					*	*

What we see here is an interesting outcome: the production form has a clear winning candidate, as we already established, but the comprehension form has two possible winners: underlying |stoˈła| or |staˈła|, because the faithfulness constraints from (8) are ranked equally. This means that a child with the SF input of /stɐ.ˈła/, does not know what the correct UF should be. This can be solved when we look at the mapping from UF to the meaning level.

4.3 Semantic mapping

The semantic mapping connects the UF and meaning, and is highlighted in the model in Figure 4.

Figure 4: Lexical mapping as part of the BiPhon model.



The contention between the two UFs, |stoˈɫa| or |staˈɫa|, that concluded the previous section, can be solved when LEXICAL constraints are involved. The general constraint (1) introduced in section 3.1, repeated below, is sufficient to make the choice for the correct UF.

(1) *‘ ’|*x*|: Assign a violation for every non-word that is mapped onto an underlying form, and vice versa.

As mentioned in 4.2.2, the GLA could explain the child’s ability to discover that a certain UF is connected to a meaning, whereas others are not. This assumption is, thus, necessary to select one UF over the other. To illustrate the choice for the mapping with the correct UF, the word recognition process is shown in Tableau 8 (on the next page). Following Boersma (2011, p. 57), the meaning (or lack thereof) is added to the candidates (from Tableau 7).

We see that in this tableau, there is only one comprehension winner, as opposed to Tableau 7. The ranking of the *‘ ’|*x*| constraint, relative to the other constraints in the tableau, is not crucial to the selection of the correct winner. Even when it is ranked the highest (as opposed to the lowest, in Tableau 8), the same winner will be selected. Although it is not unlikely that it is ranked higher than in Tableau 8. Now that the correct UF-SF pair is selected through its connection to a meaning, the child can start the orthographic production.

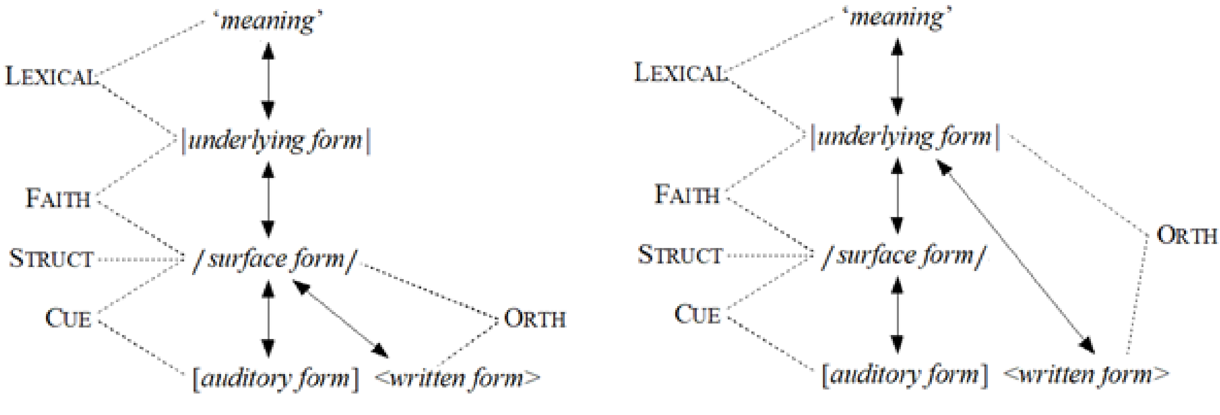
Tableau 8: Adding meaning to Tableau 7, showing the correct comprehension and production winners.

|stoˈɬa| /stɐ.ˈɬa/	V ˈ[+low]S	*/>V[sonority]S	*|ə|	*|ɐ|	|o| /o/	|ə| /ə/	|ɐ| /ɐ/	|a| /a/	*‘ ’|x|
a. ‘table’[12] |stoˈɬa| /sto.ˈɬa/	*!	****							
b. ‘table’ |stoˈɬa| /stə.ˈɬa/	*!	*			*	*			
☞ c. ‘table’ |stoˈɬa| /stɐ.ˈɬa/		**			*		*		
d. ‘table’ |stoˈɬa| /sta.ˈɬa/		***!***			*			*	
e. ‘ ’ |stəˈɬa| /stɐ.ˈɬa/		**	*!			*		*	*
f. ‘ ’ |stɐˈɬa| /stɐ.ˈɬa/		**		*!					*
g. ‘ ’ |staˈɬa| /stɐ.ˈɬa/		**					*	*	*!

4.4 Orthographic mapping

The final stage of spelling the words is the orthographic mapping. It is important to remember section 3.4 now: the orthographic mapping can occur in two routes (as shown in Figure 5). Both routes will be tested for our word. First, the sub-lexical route will be tested (§4.4.1), and afterwards, the lexical route (§4.4.2).

Figure 5: Comparing the sub-lexical route (left) to the lexical route[13] (right).



4.4.1 Sub-lexical route

Section 4.3 maps the meaning onto the UF, visualised in the top layers of the model (Figure 5). For the orthographic mapping, we have to go down a step in the model, since the

[12] The meaning of |stoˈɬa| is actually ‘table (genitive)’, as mentioned throughout this chapter, but because of considerations regarding the readability of this tableau, it is reduced to ‘table’.
[13] In their article, Hamann & Colombo (2017) discuss the lexical route, but they do so without formalising it with ORTH constraints. This paper does formalise these constraints, as introduced in (5) (§3.4), hence the depiction with the inclusion of such ORTH constraints in this figure.

orthographic mapping connects the SF to the WF. With regards to the case at hand, there are only two relevant graphemes in the Russian alphabet: <o> and <a>. This means that the four SFs {o,ə,ɐ,a} have to be mapped onto these two graphemes. This creates eight ORTH constraints, listed in (13). Tableau 9 will show that the relative ranking of these constraints is essential to determine the winner, since every candidate has the same total amount of violations. Since /o/ and /a/ can only be produced in stressed syllables, children can learn the orthographic mapping of these SFs easily, for example with monosyllabic words (with only a stressed syllable). It is then logical that /o/ would be straightforwardly mapped on <o> and not on <a>, given the choice between these two graphemes; the opposite is true for /a/. To reflect this, the constraints in (13a) and (13h) will be ranked the highest, whereas (13b) and (13g) are ranked the lowest. But these SFs are not the problem, since they are not affected by vowel reduction. The other two SFs are affected by it, and do not have such a straightforward mapping. Since /ə/ and /ɐ/ have an equal probability of being written as <o> and <a>, these four constraints (13c-f) are ranked equally, but below (13a) and (13h), and above (13b) and (13g).

(13)
a. /o/<o>: Assign a violation mark to every surface vowel /o/ that is not mapped onto the orthographic form <o>, and vice versa.

b. /o/<a>: Assign a violation mark to every surface vowel /o/ that is not mapped onto the orthographic form <a>, and vice versa.

c. /ə/<o>: Assign a violation mark to every surface vowel /ə/ that is not mapped onto the orthographic form <o>, and vice versa.

d. /ə/<a>: Assign a violation mark to every surface vowel /ə/ that is not mapped onto the orthographic form <a>, and vice versa.

e. /ɐ/<o>: Assign a violation mark to every surface vowel /ɐ/ that is not mapped onto the orthographic form <o>, and vice versa.

f. /ɐ/<a>: Assign a violation mark to every surface vowel /ɐ/ that is not mapped onto the orthographic form <a>, and vice versa.

g. /a/<o>: Assign a violation mark to every surface vowel /a/ that is not mapped onto the orthographic form <o>, and vice versa.

h. /a/<a>: Assign a violation mark to every surface vowel /a/ that is not mapped onto the orthographic form <a>, and vice versa.

Naturally, this will lead to confusion when it comes to unstressed syllables: these will always have an /ə/ or /ɐ/ in the SF, which means that (13c) will be in conflict with (13d), and that (13e) will be in conflict with (13f), since the constraints are ranked equally. In other words, the mapping between SF and WF is not sufficient for the Russian L1 learners to know what to write: there will always be multiple possible candidates. Having taken the winner from Tableau 8, we look at its SF, /stɐ.ˈɫa/, to determine the WF. This process is illustrated in Tableau 9.

Tableau 9: Surface /stɐ.ˈɫa/ to written form, using the sub-lexical route.

/stɐ.ˈɫa/	/o/ <o>	/a/ <a>	/ə/ <o>	/ə/ <a>	/ɐ/ <o>	/ɐ/ <a>	/o/ <a>	/a/ <o>
a. <столó>	**!	*	**		*	*		*
☞ b. <столá>	*		*	*		**	*	**
c. <сталó>	*	*!*	*	*	**		*	
☞ 💣 d. <сталá>		*		**	*	*	**	*

Indeed, because of the equally ranked constraints – (13c-d) on the one side and (13e-f) on the other – we find two possible candidates: <столá> and *<сталá>. This is reflected exactly in what is observed empirically in Russian children, as discussed in section 2.3: they do not know whether to write <o> or <a>, when the syllable is unstressed. The lexical route provides an outcome.

4.4.2 Lexical route

As we can see in Figure 5, contrary to the sub-lexical one, the lexical route leads directly from the WF to the UF (that is connected to a meaning), and vice versa, bypassing the phonological compartment of the model, as previously mentioned in section 3.4. This means that the SF is not of influence on the WF. Through these constraints, shown in (14), the underlying information can be used to determine the choice between <o> and <a>. This information was lost with the sub-lexical route because both UFs have the same SF.

(14) a. |o|<o>: Assign a violation mark to every underlying vowel |o| that is not mapped onto the orthographic form <o>, and vice versa.

b. |a|<a>: Assign a violation mark to every underlying vowel |a| that is not mapped onto the orthographic form <a>, and vice versa.

The two constraints are again ranked equally, as their relative ranking does not have influence on the outcome because they apply to different segments. Tableau 10 shows the mapping between the UF and the WF.

Tableau 10: Underlying |stoˈła| to written <столá>, using the lexical route.

‘table (genitive)’ |stoˈła|	|o| <o>	|a| <a>
a. <столó>	*!	*
☞ b. <столá>		
c. <сталó>	*!*	**
d. <сталá>	*!	*

In the case of the UF |stoˈla|, these mappings lead to the WF <столá>, maintaining the vowels. This UF is connected to the meaning of ‘table (genitive)’. This lexical route also brings us to the correct outcome in the comprehension direction because of the bidirectional formalisation of the constraints. Additionally, it becomes clear that, with the lexical route, the segmental orthographic mapping – as opposed to the whole-word mapping as defined by Hamann & Colombo (2017), mentioned in section 3.4 – between these forms suffices to reach the correct winning candidate.

5 Discussion

The goal of this paper was to investigate whether the BiPhon model with the orthographic component could account for the acquisition of spelling of unstressed vowels in Russian by young L1 learners of the language. Section 4 uses an example of akan’e to show that the process can indeed be modelled, and that the lexical route is necessary for this. Furthermore, it demonstrates that this route can successfully be used with ORTH constraints on segmental mappings – similar to the constraints used to map the SF onto the WF – as opposed to whole-word mappings. This benefits the application of the model, since segmental mappings can be generally applied, whereas whole-word mappings cannot, as the latter type requires a separate mapping for every lexical entry.

The ORTH constraints on segmental mapping are very much in accordance with the phonological and morphological principles by Grigorenko (2006), from section 2.3. They guide the learner towards the correct spelling based on the UF, namely the spelling when the respective vowel of the stem or morpheme is in strong position. This mapping helps the learner to correctly apply the principle, instead of spelling the vowel based on the phonetic principle – which could happen if the learner uses the SF as a guide for the spelling. However, this does not mean that Russian can be modelled without whole-word mappings. Looking back at the remaining two spelling principles, some whole-word mappings will be necessary. Some words that are (partly) spelled following the traditional principle will likely still need a whole-word mapping. For example, the <уй> (*uj*) in <пожалуйста> (from §2.3) is deleted, but this segment will not always be deleted in every word that contains it. Regarding the differentiating principle, at least one part of a pair (or two parts of a triplet, and so on) will need a whole-word mapping, as it is otherwise impossible to make a distinction between words that sound the same.

Additionally, the conclusion by Podgaevskaja and Waaijer (2013) that spelling is more difficult than reading could also be explained by the model. In this case, we have to look at reading as only reading written words out loud, setting aside comprehension. This means that the process takes the reader from the WF, through the SF, to the AF. This can be done with the sub-lexical route because the complicated choice of choosing the correct grapheme is not required. The spelling, as we have seen, needs the lexical route with the mapping between UF and WF. It seems logical that the sub-lexical route is easier to learn, as it requires fewer levels of representation. This would explain why children can read out loud before they can spell correctly.

It is, however, important to note that the assumption that the children are successful in learning how to determine the correct underlying form is crucial to the application of the model to Russian vowel reduction. Section 4.2.2 uses the GLA to account for this necessary process. In the case of Russian, the GLA can also be facilitated by using the information from vowels in stressed position for the same vowels when they are in unstressed position, as a consequence of the moving stress due to inflection (Kerek & Niemi, 2009). This gives the assumption more credibility, but in order to gain more evidence for it, perhaps experimental research is needed.

What the analysis in this paper also does not reflect, is the observation that the vowels in inflectional morphemes are learnt quicker than the “arbitrary” vowels in stems (Stepanova, 2009). The present analysis does not distinct between these vowels. More thorough future research into this topic may attempt to model this distinction, where these morphological units, like affixation, could perhaps have earlier access to the lexical route than other morphemes. This might require some lexical constraints regarding affixes that rank up quicker than the lexical constraint on non-words that was used in this paper. Future research could also contain more aspects of vowel reduction, e.g., different vowels and effect of palatalised consonants, to investigate whether the model can still account for this and if the ORTH constraints on segmental mappings still suffice in these cases.

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