Akanje and Optimality Theory

Employing the bidirectional grammar model BiPhon

to analyse one case of vowel reduction in Russian

Anastasia Shchupak 13298321

BA Linguistics

Linguistic theories

Supervisor: Dr. Titia Benders

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1. Introduction: What is Akanje?

In the context of East Slavic dialects, the term ‘vowel reduction’ is traditionally used to refer to a variety of vowel neutralization patterns in unstressed syllables. This paper will focus on one specific neutralisation pattern involving the neutralisation of the phonemes /a/ and /o/ in non-palatalised contexts. There are different ways to treat unstressed /a/ and /o/ in East Slavic dialects, including the numerous dialects of Russian. Speakers of some dialects distinguish them when pronouncing [soˈva] ‘owl’ and [traˈva] ‘grass’, while speakers of other dialects, including Standard Russian, lose this distinction when pronouncing [saˈva] and [traˈva], or perhaps [sɐˈva] and [trɐˈva]. This lack of differentiation between /a/ and /o/ is typically referred to as Akanje (Lunt 1980).

2. Existing analyses of Akanje

Traditional Russian phonology suggests that the phonemes /a/ and /o/ appear at the surface form in accented syllables as [a] and [o] respectively, while in unaccented syllables they are both reduced to either [ɐ] or schwa. [ɐ] is found in immediately pre-tonic position and schwa in other pre-tonic and posttonic positions. Such phonological representation applied to two and three syllable words with the stress on the last syllable, which are the focus of the current paper, is demonstrated in the examples (1a) – (1d).

(1) *Two different realisations of the same phonemes*

a.	/s**o**va/[s**ɐ**ˈva]	‘owl’
b.	/s**a**mo/ [s**ɐ**ˈmo]	‘itself’
c.	/g**olo**va/ [g**əɫɐ**ˈva]	‘head’
d.	/p**ara**doks/ [p**ərɐ**ˈdoks]	‘paradox’

One method of analysing these two patterns was proposed by Crosswhite (2000a, 2000b). Using the observation that reduced duration typically causes lowering in vowel sonority, she suggests using the sonority scale as well as the foot form and the processes of lengthening under stress, to account for two distinct phonological categories of reduction: “extreme” and “moderate”. Interestingly, according to Crosswhite, her analysis demonstrates that the two different phonological patterns are in fact phonetically motivated (Crosswhite 2000b: 154). However, the nature of the standard two-level phonological model does not leave a special place for phonetics and invites researchers to include phonetic processes to the surface level representation, referring to them as to phonological processes.

In a more recent research, Barnes (2007) proposes to have a clearer distinction between phonetic and phonological processes of Russian vowel reduction and contends that neutralization of /a/ and /o/ to [a] in Russian unstressed syllables is a pure phonological process, triggered by stress as an abstract structural factor, and therefore not motivated phonetically. This process is followed by further raising of [a] to schwa in the syllables which undergo "extreme" reduction in the terminology of Crosswhite (2000a), as well as raising of [a] to [ɐ] in the syllables which undergo "moderate" reduction. The process of raising is driven by phonetics, namely by reduced duration of the vowel causing an articulatory challenge for pronouncing a peripheral low vowel.

Barnes' suggestion has not yet been examined within the Optimality Theory framework, probably because there is no obvious method to specifically account for a gradual phonetic process using the conventional two-level phonological model. Tableau (2) represents an attempt to do so. The phonological process of reduction described by Barnes can be implemented with the use of the markedness constraint *[o]$_{NS}$, meaning the phoneme [o] is not allowed in unstressed syllables at the surface level. But how can we encode a phonetic process which ensures a gradual raising of [a]? Using the markedness constraint [+low] $_{NS}$, we can explain the appearance of such allophones of [a] a as [ɐ] and schwa in the surface form. However, making a choice between the candidates in [gɐlɐˈva], [gəlɐˈva], and [gələˈva] is problematic without an acoustic information, such as vowel duration.

(2) *Production in two-level phonological model*

/golova/	*[o]$_{NS}$	[+low] $_{NS}$	IDENT-IO (V)
[goloˈva]	**!		
[galaˈva]		**!	**
☞ [gɐlɐˈva]			**
☞ [gəlɐˈva]			**
☞ [gələˈva]			**

Tableau (3) demonstrates the second issue with the two-level phonological paradigm, which occurs when we attempt to model comprehension. We apply the same constraints for this modelling since Smolensky (Smolensky 1996, in: Boersma 2009) showed that the mapping from underlying to surface form may be reversed for modelling comprehension by utilizing the same constraints with the same ranking. Since markedness constraints control the input in the situation of comprehension and will therefore never be violated, only the faithfulness constraints are in effect in tableau (3). However, faithfulness constraints by their nature aim to avoid any change, thus our best candidate will be the underlying form, which is as similar to the surface form as is guaranteed by the faithfulness constraints. In other words, the listener has no means of mapping the sound [gəlɐˈva] to the underlying form /golova/.

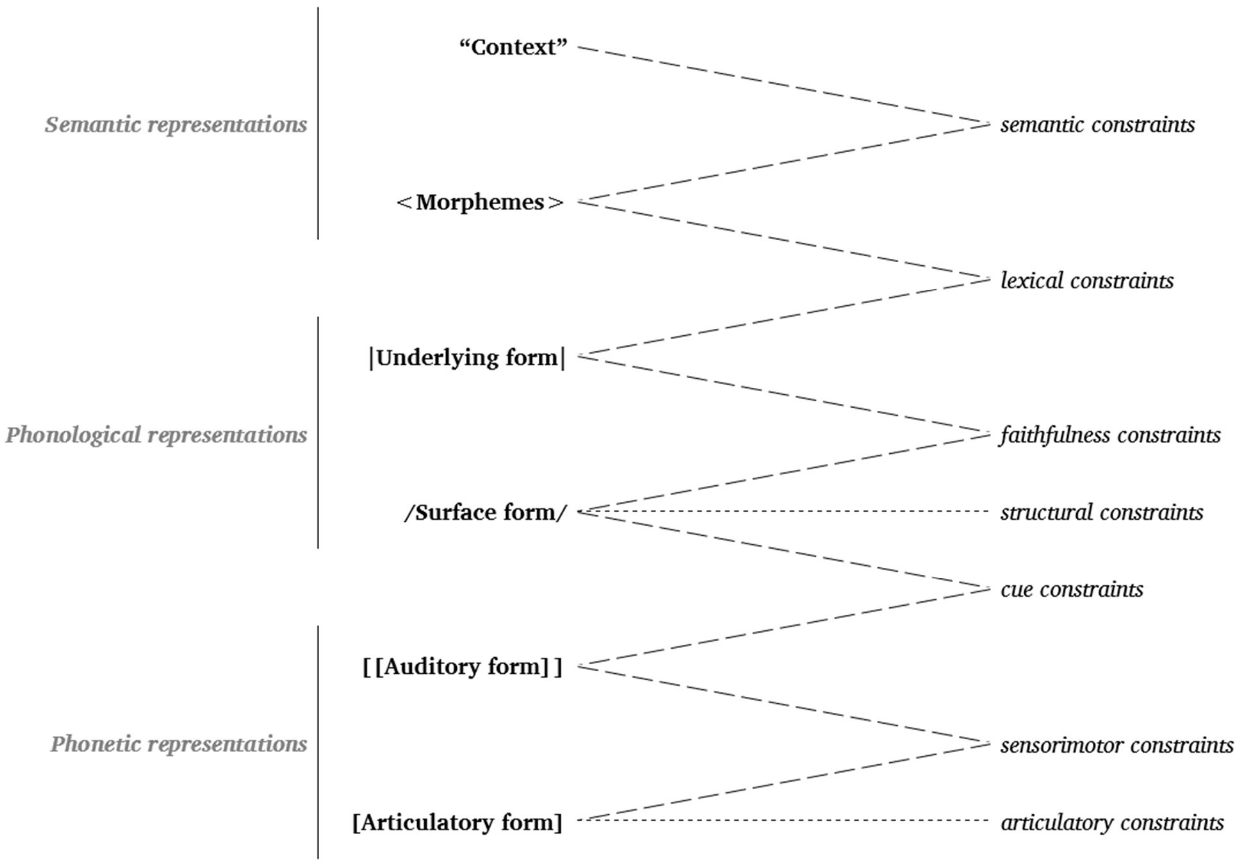
(3) *Comprehension in two-level phonological model*

[gəlɐˈva]	$*[o]_{NS}$	$[+low]_{NS}$	IDENT-IO (V)
/golova/			**!
/galava/			**!
☞ /gəlɐva/			

From the two reported problems, it is evident that more levels than just phonological are required to model Akanje, especially if we want to account for both perception and production. Phonetic level is necessary to model the phonetic process involved in differentiating unstressed vowels. Semantic level can assist in choosing the proper underlying form during the comprehension process. Bidirectional grammar model BiPhon, presented by Boersma (2009, 2011), is a phonological model that includes all the levels described and more. The following sections of this paper will first introduce and then employ BiPhon in an effort to model production and comprehension of the Contemporary Standard Russian Akanje. I predict that there is an analysis that will work since BiPhon model takes phonetics, semantics, and their interactions with phonology into consideration.

3. Six-level BiPhon model

An Optimality-Theoretic grammar model presented by Boersma (2011) and shown in the Figure 1 establishes a clear distinction between three levels of processing: semantic, phonological, and phonetic. With the use of this approach, it is possible to clearly separate phonological processes from those that may affect phonological representations but are not inherently phonological themselves. In other words, it removes semantics and phonetics from the domain of phonology, increasing the overall number of levels of processing while greatly reducing the complexity of each individual level.



Picture 1. BiPhon grammar model

Extracting semantics from phonology was in fact already proposed by Hale and Reiss (1998, in: Boersma 2011), when they noted the problem in identifying the correct underlying form for homophones during comprehension. They suggested that the list of underlying form candidates should be disambiguated higher up by syntactic, semantic, and pragmatic processing. Their idea can be formalized thanks to the use of a distinct semantic level that is a component of BiPhon grammatical model.

The argument for separating phonetics and phonology is easy to make. It is sufficient to remember that phonological processes are intrinsically categorical, whereas phonetic processes are continuous by nature. It is therefore sensible to get around the difficulty of creating rules that would regulate both discrete and continuous processes on the same level by splitting them into two independent levels, isolating complexity to the interface between them.

BiPhon model uses six levels of representation, from which two are semantic ("Context" and <Morphemes>), two are phonological (|Underlying| and /Surface/ forms), and two are phonetic ([[Auditory]] and [Articulatory] forms). Each of the six levels is connected to its adjacent levels by specific sets of constraints, as shown in Figure 1. Only two levels have constraints that are situated within the level rather than on the boundary between it and the neighbouring level, namely phonological surface form with the set of structural constraints and phonetic articulatory form with the set of articulatory constraints. In the two-level phonological OT model, we would refer to structural constraints as markedness constraints. However, the domain of markedness constraints typically includes phonetic processes, whereas the presence of the distinct phonetic level in BiPhon enables us to restrict this domain to specifically phonological structural processes.

Two important characteristics of Biphon model are parallelism and bidirectionality. Parallelism refers to the interplay between all constraints, or, put another way, to the fact that all constraints take part in a single global ranking. Bidirectionality refers to the use of the same constraints and their rankings for both the comprehension and production processes.

It is important to note a slight change in notation for phonological forms. Instead of the conventional // and [], underlying and surface forms are denoted using || and //, respectively, leaving the square brackets for the phonetic representations. Current paper from now on will use this new notation. Moreover, I will employ a somewhat simplified version of this model, combining auditory and articulatory forms together into a single [Phonetic form]. This implies that sensorimotor constraints will be disregarded, or, to put it another way, their ranking will be so high that the auditory and articulatory forms will be identical. In semantic representations, I will ignore the “Context” level and therefore semantic constraints that connect it to the <Morphemes>. With these simplifications, a six-level model will be reduced to a four-level model, which will be sufficient for my analysis.

4. Phonology-phonetics interface

We will now go back to the topic of the Contemporary Standard Russian Akanje and attempt to use BiPhon model to analyse the findings of Barnes (2007), which were discussed in section 2. One of Barnes' experiments focussed on analysing the connection between vowel quality (specifically, the first formant) and vowel duration in the underlying |a| and |o| in tonic, first pretonic, and second pretonic syllables (Barnes 2006, in Barnes 2007). In our modelling, we will use the acoustic data which he collected during this experiment. With the help of this data we will create cue constraints: the main instrument of mapping acoustic data to phonological categories.

4.1. Acoustic data

Table 1 shows the mean values and standard deviations for the first formants and durations of the underlying |a| and |o| obtained by Barnes in his experiment (Barnes 2006, in Barnes 2007). Our goal will be to demonstrate how this data can be mapped to the phonological categories (phonemes). Given that I am not using computer simulation for this research, my objective is to somewhat simplify the data to make it manageable while retaining any information that would suggest a different categorisation. The steps for such simplification are described below.

Table 1. Mean F1 and duration values for underlying vowels |a| and |o| with their standard deviations

	F1 (Hz)		Duration (ms)	
	|a|	|o|	|a|	|o|
2nd pretonic	475 (52)	481 (55)	25.2 (9.2)	28.9 (9.7)
1st pretonic	705 (68.5)	694 (73)	69 (16.9)	69.9 (16.2)
tonic	700 (78)	461 (39)	81.8 (19.3)	74.5 (21.5)

First pretonic |a| and |o| exhibit very small and not significant differences in F1 and duration. The same observation goes for second pretonic |a| and |o|. This indicates that acoustically there is no way a listener can categorise the sound in the first pretonic position into two different categories, and the same goes for the second pretonic position. Therefore, I will simplify the finding of Barnes, taking approximate values for F1 and duration for the first and the second pretonic positions, as indicated in the Table 2.

Table 2. Mean F1 and duration values for underlying vowels |a| and |o| with their standard deviations

	F1	Vowel duration
2nd pretonic (|a| or |o|)	470 Hz	25 ms
1st pretonic (|a| or |o|)	700 Hz	70 ms
tonic |a|	700 Hz	80 ms
tonic |o|	470 Hz	70 ms

Furthermore, the F1 value of tonic |o| can be approximated to 470 Hz (instead of 461 Hz), because it will not influence the categorical difference, but will help us to maintain the variety of input when we will start building the interface between acoustic data and phonological representation. In fact, the F1 for both second pretonic vowels and for the tonic |o| is now the same, but the duration is different, which will allow the listener to categorise them into two different phonemes. Following the same logic, I approximate the duration of the tonic |o| to 70 ms (instead of 74.5 ms). However, I am going to keep the difference in duration between the first pretonic vowel and tonic |a|, because they coincide in their F1 value, and even the slight difference in duration can appear categorical. It is important to note, that in real life there might be more clear acoustic cues helping a listener to categorise between the first pretonic vowel and tonic |a|, but as our model is resorting to only F1, we will use this difference as a main categorisation cue.

4.2. Modelling perception: cue constraints

As was previously mentioned, the primary tool for mapping phonetic data to phonological categories is cue constraints. Table 3, which is essentially a slightly reorganized Table 2 with a new column for the surface form phonemes, will be used to create them. We need the column with the surface form phonemes, to specify the desirable mapping. The subscript NT in the notation of the phoneme $/a/_{NT}$ means "not tonic" or "not stressed", and the subscript T in the notation of the phonemes $/o/_{T}$ and $/a/_{T}$ means "tonic" or "stressed".

Table 3. Mean F1 and duration values for underlying vowels |a| and |o| with their standard deviations

	F1	Vowel duration	Surface form
2nd pretonic (|a| or |o|)	470 Hz	25 ms	$/a/_{NT}$
tonic |o|		70 ms	$/o/_{T}$
1st pretonic (|a| or |o|)	700 Hz	70 ms	$/a/_{NT}$
tonic |a|		80 ms	$/a/_{T}$

In the table 3 we can see that we are going to map three distinct sounds [470Hz, 25ms], [700Hz, 70ms] and [700Hz, 80ms] to one phoneme /a/. It is important to note, that $/a/_{NT}$ and $/a/_{T}$ are not two different phonemes, but $/a/_{T}$ will appear in surface forms with the stress (/ˈa/), whereas $/a/_{NT}$ will appear in surface forms without the stress (/a/). I chose the subscript notation for the representational clarity when using phonemes in isolation, but later in the analysis of example words, I am going to use traditional stress sign instead.

The decision to use a single phoneme rather than two or three different allophones for each of the three different positions of /a/ in relation to the stressed syllable is backed up by the findings of Barnes (2006, 2007). In his research, he demonstrated that whereas the rising to schwa in second pretonic syllables is more of a continuous process driven by the articulatory limitations, the reduction of |o| and |a| to /a/ is categorical. Additionally, he showed that the first pretonic /a/

does not exhibit a particularly stable difference from the tonic /a/ in terms of acoustic properties. Based on this observation, I will assume in my modelling that there is no phonological distinction between first and second pretonic /a/ as well as between them and tonic /a/.

Our cue constraints will take the form */X/[AudCue], which means that a sound with the auditory cue [AudCue] cannot map to the phoneme /X/. The cue constraints I will use to begin my modelling are all listed in Table 4. I divided them in three groups to show the initial ranking, with the following motivation. Constraints in the high-ranked group may prevent mapping of the sound to the wrong category. Constraints in the low-ranked group should not interfere with the mapping to the right category. The middle-ranked group of constraints is formed by the unstressed $/a/_{NT}$. The reason for it is that we want to map two sounds with very distinct auditory cues ([470Hz, 25ms] and [700Hz, 70ms]) to the same phoneme $/a/_{NT}$. The only acoustic quality which can not be mapped to $/a/_{NT}$ is [80ms], that is why the constraint $*/a/_{NT}$[80ms] is in the high-ranked group.

Table 4. Cue constraints

High-ranked		Middle-ranked		Low-ranked	
F1	Duration	F1	Duration	F1	Duration
$*/a/_{T}$[470Hz] $*/o/_{T}$[700Hz]	$*/a/_{NT}$[80ms] $*/a/_{T}$[25ms] $*/a/_{T}$[70ms] $*/o/_{T}$[25ms] $*/o/_{T}$[80ms]	$*/a/_{NT}$[700Hz] $*/a/_{NT}$[470Hz]	$*/a/_{NT}$[70ms] $*/a/_{NT}$[25ms]	$*/a/_{T}$[700Hz] $*/o/_{T}$[470Hz]	$*/a/_{T}$[80ms] $*/o/_{T}$[70ms]

In my modelling, I will start with preserving these three groups intact, meaning that the constraints within one group will have the equal ranking, and there will be between-group ranking: *High-ranked group* > > *Middle-ranked group* > > *Low-ranked group*. I will also use the structural constraint $*/o/_{NT}$ ranked very high, which is not allowing unstressed /o/ in the surface form, and which is essentially the main phonological feature of Akanje. Important note is that in my modelling tableaus I will use the notation proposed by Boersma (2011): the finger will point backwords to mark the candidate that wins in the comprehension direction. I start my modelling with perception of individual sounds, which is shown in the tableaus (4) – (7), one tableau per possible sound.

(4) *Perception of the sound [470Hz, 25ms]*

[470Hz, 25ms]	*/o/$_{NT}$	*/a/$_{T}$ [470Hz]	*/o/$_{T}$ [700Hz]	*/a/$_{NT}$ [80ms]	*/a/$_{T}$ [25ms]	*/a/$_{T}$ [70ms]	*/o/$_{T}$ [25ms]	*/o/$_{T}$ [80ms]	*/a/$_{NT}$ [470Hz]	*/a/$_{NT}$ [25ms]	*/a/$_{NT}$ [700Hz]	*/a/$_{NT}$ [70ms]	*/o/$_{T}$ [470Hz]	*/o/$_{T}$ [70ms]	*/a/$_{T}$ [700Hz]	*/a/$_{T}$ [80ms]
☜/a/$_{NT}$[470Hz, 25ms]									*	*						
/a/$_{T}$[470Hz, 25ms]		*!			*											
/o/$_{NT}$[470Hz, 25ms]	*!															
/o/$_{T}$[470Hz, 25ms]							*!						*			

(5) *Perception of the sound [470Hz, 70ms]*

[470Hz, 70ms]	*/o/$_{NT}$	*/a/$_{T}$ [470Hz]	*/o/$_{T}$ [700Hz]	*/a/$_{NT}$ [80ms]	*/a/$_{T}$ [25ms]	*/a/$_{T}$ [70ms]	*/o/$_{T}$ [25ms]	*/o/$_{T}$ [80ms]	*/a/$_{NT}$ [470Hz]	*/a/$_{NT}$ [25ms]	*/a/$_{NT}$ [700Hz]	*/a/$_{NT}$ [70ms]	*/o/$_{T}$ [470Hz]	*/o/$_{T}$ [70ms]	*/a/$_{T}$ [700Hz]	*/a/$_{T}$ [80ms]
/a/$_{NT}$[470Hz, 70ms]									*!			*				
/a/$_{T}$[470Hz, 70ms]		*!				*										
/o/$_{NT}$[470Hz, 70ms]	*!															
☜/o/$_{T}$[470Hz, 70ms]													*	*		

(6) *Perception of the sound [700Hz, 70ms]*

[700Hz, 70ms]	*/o/$_{\text{NT}}$	*/a/$_{\text{T}}$[470Hz]	*/o/$_{\text{T}}$[700Hz]	*/a/$_{\text{NT}}$[80ms]	*/a/$_{\text{T}}$[25ms]	*/a/$_{\text{T}}$[70ms]	*/o/$_{\text{T}}$[25ms]	*/o/$_{\text{T}}$[80ms]	*/a/$_{\text{NT}}$[470Hz]	*/a/$_{\text{NT}}$[25ms]	*/a/$_{\text{NT}}$[700Hz]	*/a/$_{\text{NT}}$[70ms]	*/o/$_{\text{T}}$[470Hz]	*/o/$_{\text{T}}$[70ms]	*/a/$_{\text{T}}$[700Hz]	*/a/$_{\text{T}}$[80ms]
/a/$_{\text{NT}}$[700Hz, 70ms]											*	*				
/a/$_{\text{T}}$[700Hz, 70ms]						*!									*	
/o/$_{\text{NT}}$[700Hz, 70ms]	*!															
☜/o/$_{\text{T}}$[700Hz, 70ms]			*!											*		

(7) *Perception of the sound [700Hz, 80ms]*

[700Hz, 80ms]	*/o/$_{\text{NT}}$	*/a/$_{\text{T}}$[470Hz]	*/o/$_{\text{T}}$[700Hz]	*/a/$_{\text{NT}}$[80ms]	*/a/$_{\text{T}}$[25ms]	*/a/$_{\text{T}}$[70ms]	*/o/$_{\text{T}}$[25ms]	*/o/$_{\text{T}}$[80ms]	*/a/$_{\text{NT}}$[470Hz]	*/a/$_{\text{NT}}$[25ms]	*/a/$_{\text{NT}}$[700Hz]	*/a/$_{\text{NT}}$[70ms]	*/o/$_{\text{T}}$[470Hz]	*/o/$_{\text{T}}$[70ms]	*/a/$_{\text{T}}$[700Hz]	*/a/$_{\text{T}}$[80ms]
/a/$_{\text{NT}}$[700Hz, 80ms]				*!							*					
/a/$_{\text{T}}$[700Hz, 80ms]															*	*
/o/$_{\text{NT}}$[700Hz, 80ms]	*!															
☜/o/$_{\text{T}}$[700Hz, 80ms]			*!					*								

Tableaus (4) – (7) demonstrate the working of the initial ranking: [470Hz, 25ms] is mapped to /a/$_{NT}$, [470Hz, 70ms] is mapped to /o/$_{T}$, [700Hz, 70ms] is mapped to /a/$_{NT}$, and [700Hz, 80ms] is mapped to /a/$_{T}$. This means, we can proceed to modelling production.

4.3. Modelling production: adding articulatory constraints

My initial, unsuccessful attempt to model the production of the phoneme /a/$_{NT}$ is shown in Tableau (8). There are four winning candidates, and each of them violates two constraints equally ranked. We could predict this problem occurring since we mapped two distinct sounds into one phoneme. Obviously, reversing the process from perception to production, we will need to find the way to realise one phoneme as two different sounds.

(8) *Production of /a/$_{NT}$ first attempt*

/a/$_{NT}$	*/a/$_{T}$ [470 Hz]	*/o/$_{T}$ [700 Hz]	*/a/$_{NT}$ [80 ms]	*/a/$_{T}$ [25 ms]	*/a/$_{T}$ [70 ms]	*/o/$_{T}$ [25 ms]	*/o/$_{T}$ [80 ms]	*/a/$_{NT}$ [470 Hz]	*/a/$_{NT}$ [25 ms]	*/a/$_{NT}$ [700 Hz]	*/a/$_{NT}$ [70 ms]	*/o/$_{T}$ [470 Hz]	*/o/$_{T}$ [70 ms]	*/a/$_{T}$ [700 Hz]	*/a/$_{T}$ [80 ms]
☞/a/$_{NT}$[470Hz, 25ms]								*	*						
☞/a/$_{NT}$[470Hz, 70ms]								*			*				
/a/$_{NT}$[470Hz, 80ms]			*!					*							
☞/a/$_{NT}$[700Hz, 25ms]									*	*					
☞/a/$_{NT}$[700Hz, 70ms]										*	*				
/a/$_{NT}$[700Hz, 80ms]			*!							*					

I am going to fix the problem which we observe in tableau (8) in two steps. First, I will change the ranking of the initially middle-ranked constraints, moving the constraints */a/$_{NT}$[700Hz] and */a/$_{NT}$[70ms] to the low-ranked group, as it is shown in tableau (9). By this step, I want to indicate that by default */a/$_{NT}$ should be produced as the sound [700Hz, 70ms], how it is pronounced in the first pretonic syllable. And only in case of the second pretonic syllable, motivated by articulatory restrictions, which I will describe below, */a/$_{NT}$ is produced as the sound [470Hz, 25ms]. As tableau (9) shows, this reranking will make /a/$_{NT}$ always sound as [700Hz, 70ms].

(9) *Production of /a/$_{NT}$ second attempt*

/a/$_{NT}$	*/a/$_{T}$ [470 Hz]	*/o/$_{T}$ [700 Hz]	*/a/$_{NT}$ [80 ms]	*/a/$_{T}$ [25 ms]	*/a/$_{T}$ [70 ms]	*/o/$_{T}$ [25 ms]	*/o/$_{T}$ [80 ms]	*/a/$_{NT}$ [470 Hz]	*/a/$_{NT}$ [25 ms]	*/a/$_{NT}$ [700 Hz]	*/a/$_{NT}$ [70 ms]	*/o/$_{T}$ [470 Hz]	*/o/$_{T}$ [70 ms]	*/a/$_{T}$ [700 Hz]	*/a/$_{T}$ [80 ms]
/a/$_{NT}$[470Hz, 25ms]								*!	*						
/a/$_{NT}$[470Hz, 70ms]								*!			*				
/a/$_{NT}$[470Hz, 80ms]			*!					*							
/a/$_{NT}$[700Hz, 25ms]									*!	*					
☞/a/$_{NT}$[700Hz, 70ms]										*	*				
/a/$_{NT}$[700Hz, 80ms]			*!							*					

Tableau (9) makes it clear that we need to differentiate between the second and the first pretonic syllables. I will introduce a new notation for that: the subscript 2PT in the notation of the phoneme $/a/_{2PT}$ means “second pretonic”, and the subscript 1PT in the notation of the phoneme $/a/_{1PT}$ means “first pretonic”. To account for the fact that the second pretonic syllable is shorter than the first, I add a cue constraint which will prevent second pretonic syllable being long: $*/X/_{2PT}$ [long]. Then, I introduce an articulatory constraint: *[low, short], which will militate against short vowels being low. For our data, values 25ms falls into a short category and 70-80ms into a long one. Tableau (10) shows the production of $/a/_{2PT}$ using new constraints.

(10) *Production of* $/a/_{2PT}$

$/a/_{2PT}$	$*[\text{low, short}]_{ART}$	$*/X/_{2PT}$ [long]	$*/a/_{T}$ [470 Hz]	$*/o/_{T}$ [700 Hz]	$*/a/_{NT}$ [80 ms]	$*/a/_{T}$ [25 ms]	$*/a/_{T}$ [70 ms]	$*/o/_{T}$ [25 ms]	$*/o/_{T}$ [80 ms]	$*/a/_{NT}$ [470 Hz]	$*/a/_{NT}$ [25 ms]	$*/a/_{NT}$ [700 Hz]	$*/a/_{NT}$ [70 ms]	$*/o/_{T}$ [470 Hz]	$*/o/_{T}$ [70 ms]	$*/a/_{T}$ [700 Hz]	$*/a/_{T}$ [80 ms]
☞$/a/_{2PT}$[470Hz, 25ms]										*	*						
$/a/_{2PT}$[470Hz, 70ms]		*!								*			*				
$/a/_{2PT}$[470Hz, 80ms]		*!			*					*							
$/a/_{2PT}$[700Hz, 25ms]	*!										*	*					
$/a/_{2PT}$[700Hz, 70ms]		*!										*	*				
$/a/_{2PT}$[700Hz, 80ms]		*!			*							*					

Tableaus (11) – (13) show the production of $/a/_{1PT}$, $/a/_{T}$, and $/o/_{T}$.

(11) *Production* $/a/_{1PT}$

$/a/_{1PT}$	*[low, short]$_{ART}$	$*/X/_{2PT}$[long]	$*/a/_{T}$[470 Hz]	$*/o/_{T}$[700 Hz]	$*/a/_{NT}$[80 ms]	$*/a/_{T}$[25 ms]	$*/a/_{T}$[70 ms]	$*/o/_{T}$[25 ms]	$*/o/_{T}$[80 ms]	$*/a/_{NT}$[470 Hz]	$*/a/_{NT}$[25 ms]	$*/a/_{NT}$[700 Hz]	$*/a/_{NT}$[70 ms]	$*/o/_{T}$[470 Hz]	$*/o/_{T}$[70 ms]	$*/a/_{T}$[700 Hz]	$*/a/_{T}$[80 ms]
$/a/_{1PT}$[470Hz, 25ms]										*!	*						
$/a/_{1PT}$[470Hz, 70ms]										*!			*				
$/a/_{1PT}$[470Hz, 80ms]					*!					*							
$/a/_{1PT}$[700Hz, 25ms]	*!										*	*					
☞$/a/_{1PT}$[700Hz, 70ms]												*	*				
$/a/_{1PT}$[700Hz, 80ms]					*!							*					

(12) *Production of* $/a/_T$

$/a/_T$	*[low, short]$_{ART}$	*/X/$_{2PT}$[long]	*/a/$_T$[470 Hz]	*/o/$_T$[700 Hz]	*/a/$_{NT}$[80 ms]	*/a/$_T$[25 ms]	*/a/$_T$[70 ms]	*/o/$_T$[25 ms]	*/o/$_T$[80 ms]	*/a/$_{NT}$[470 Hz]	*/a/$_{NT}$[25 ms]	*/a/$_{NT}$[700 Hz]	*/a/$_{NT}$[70 ms]	*/o/$_T$[470 Hz]	*/o/$_T$[70 ms]	*/a/$_T$[700 Hz]	*/a/$_T$[80 ms]
$/a/_T$[470Hz, 25ms]			*!			*											
$/a/_T$[470Hz, 70ms]			*!				*										
$/a/_T$[470Hz, 80ms]			*!														*
$/a/_T$[700Hz, 25ms]	*!					*										*	
$/a/_T$[700Hz, 70ms]							*!									*	
☞$/a/_T$[700Hz, 80ms]																*	*

(13) *Production of* /o/$_{T}$

/o/$_{T}$	*[low, short]$_{ART}$	*/X/$_{2PT}$[long]	*/a/$_{T}$[470 Hz]	*/o/$_{T}$[700 Hz]	*/a/$_{NT}$[80 ms]	*/a/$_{T}$[25 ms]	*/a/$_{T}$[70 ms]	*/o/$_{T}$[25 ms]	*/o/$_{T}$[80 ms]	*/a/$_{NT}$[470 Hz]	*/a/$_{NT}$[25 ms]	*/a/$_{NT}$[700 Hz]	*/a/$_{NT}$[70 ms]	*/o/$_{T}$[470 Hz]	*/o/$_{T}$[70 ms]	*/a/$_{T}$[700 Hz]	*/a/$_{T}$[80 ms]
/o/$_{T}$[470Hz, 25ms]								*!						*			
☞/o/$_{T}$[470Hz, 70ms]														*	*		
/o/$_{T}$[470Hz, 80ms]									*!					*			
/o/$_{T}$[700Hz, 25ms]	*!			*				*									
/o/$_{T}$[700Hz, 70ms]				*!											*		
/o/$_{T}$[700Hz, 80ms]				*!					*								

As can be seen in the tableaus (10) – (13), production of individual phonemes is now working good: /a/$_{2PT}$ is produced as [470Hz, 25ms], /a/$_{1PT}$ is produced as [700Hz, 70ms], /a/$_{T}$ is produced as [700Hz, 80ms], and /o/$_{T}$ is produced as [470Hz, 70ms]. Now it is time to apply the established analysis to the example words.

4.4. Applying the analysis: examples

Using the ranking of cue and articulatory constraints established in the previous sections, I will run this analysis on example words, first for perception and then for production. Perception tableaus (14) – (17) demonstrate how the stress enters phonology from acoustic data. The list of candidates contains not only the different permutations of the possible phonemes /a/ and /o/, but also all the stress patterns for every permutation.

(14) *Perception:* /.sa.ˈva./

[s***X***v***Y***] ***X*** = [700Hz, 70ms] ***Y*** = [700Hz, 80ms]	/*o/ NT	*/a/ T [470 Hz]	*/o/ T [700 Hz]	*/a/ NT [80 ms]	*/a/ T [25 ms]	*/a/ T [70 ms]	*/o/ T [25 ms]	*/o/ T [80 ms]	*/a/ NT [470 Hz]	*/a/ NT [25 ms]	*/a/ NT [700 Hz]	*/a/ NT [70 ms]	*/o/ T [470 Hz]	*/o/ T [70 ms]	*/a/ T [700 Hz]	*/a/ T [80 ms]
/.ˈsa.va./[s***X***v***Y***]				*!		*					*				*	
☜/.sa.ˈva./[s***X***v***Y***]											*	*			*	*
/.ˈso.va./[s***X***v***Y***]			*!	*							*			*		
/.so.ˈva./[s***X***v***Y***]	*!														*	*
/.ˈsa.vo./[s***X***v***Y***]	*!					*									*	
/.sa.ˈvo./[s***X***v***Y***]			*!					*								
/.ˈso.vo./[s***X***v***Y***]	*!		*											*		
/.so.ˈvo./[s***X***v***Y***]	*!		*					*								

I do not include the articulatory constraint *[low, short]$_{ART}$ and the cue constraint */X/2PT [long] to the perception tableaus (14) – (17) to save space, because in this case they are restricting the input and will never be violated.

(15) *Perception: /.sa.ˈmo./*

[s***X***m***Y***] ***X*** = [700Hz, 70ms] ***Y*** = [470Hz, 70ms]	/*o/ NT	*/a/ T [470 Hz]	*/o/ T [700 Hz]	*/a/ NT [80 ms]	*/a/ T [25 ms]	*/a/ T [70 ms]	*/o/ T [25 ms]	*/o/ T [80 ms]	*/a/ NT [470 Hz]	*/a/ NT [25 ms]	*/a/ NT [700 Hz]	*/a/ NT [70 ms]	*/o/ T [470 Hz]	*/o/ T [70 ms]	*/a/ T [700 Hz]	*/a/ T [80 ms]
/.ˈsa.ma./[s***X***m***Y***]						*!			*			*			*	
/.sa.ˈma./[s***X***m***Y***]		*!				*						*			*	
/.ˈso.ma./[s***X***m***Y***]			*!						*			*		*		
/.so.ˈma./[s***X***m***Y***]	*!	*				*										
/.ˈsa.mo./[s***X***m***Y***]	*!					*									*	
☜/.sa.ˈmo./[s***X***m***Y***]												*	*	*	*	
/.ˈso.mo./[s***X***m***Y***]	*!		*											*		
/.so.ˈmo./[s***X***m***Y***]	*!												*	*		

The number of all possible candidates is very big for tableau (16). To save some space, I will reduce the number of candidates. To do this, I will refer to tableau (14) which mapped two incoming sounds [700Hz, 70ms] and [700Hz, 80ms] to the optimal surface form /.sa.ˈva./. The incoming sounds in the tableau (16) is [470Hz, 25ms], [700Hz, 70ms] and [700Hz, 80ms], where the last two sounds are the same as the input sounds in the tableau (14), for which the optimal surface form was already found: /a/$_{NT}$ and /a/$_{T}$. Therefore, I will preselect only the candidates that are ending with /.la.ˈva./ in the tableau (16), which makes us only choose the optimal first syllable.

(16) *Perception: /ga.la.ˈva./*

[g***X***l***Y***v***Z***] ***X*** = [470Hz, 25ms] ***Y*** = [700Hz, 70ms] ***Z*** = [700Hz, 80ms]	/*o/$_{NT}$	*/a/$_{T}$ [470Hz]	*/o/$_{T}$ [700Hz]	*/a/$_{NT}$ [80ms]	*/a/$_{T}$ [25ms]	*/a/$_{T}$ [70ms]	*/o/$_{T}$ [25ms]	*/o/$_{T}$ [80ms]	*/a/$_{NT}$ [470Hz]	*/a/$_{NT}$ [25ms]	*/a/$_{NT}$ [700Hz]	*/a/$_{NT}$ [70ms]	*/o/$_{T}$ [470Hz]	*/o/$_{T}$ [70ms]	*/a/$_{T}$ [700Hz]	*/a/$_{T}$ [80ms]
☜/.ga.la.ˈva./[g***X***l***Y***v***Z***]									*	*	*	*			*	*
/.go.la.ˈva./[g***X***l***Y***v***Z***]	*!										*	*			*	*

Reducing the list of candidates for tableau (17) will work in the same way as it worked for tableau (16). Tableau (15) has already found the optimal candidate for the input sounds [700Hz, 70ms] and [470Hz, 70ms], which are */a/$_{NT}$ and /o/$_{T}$*. Therefore, I will preselect only the candidates that are ending with /.ra.ˈdoks./ in the tableau (17), which makes us only choose the optimal first syllable.

(17) *Perception: /pa.ra.ˈdoks./*

[p***X***p***Y***d***Z***ks] ***X*** = [470Hz, 25ms] ***Y*** = [700Hz, 70ms] ***Z*** = [470Hz, 70ms]	/*o/$_{NT}$	*/a/$_{T}$ [470 Hz]	*/o/$_{T}$ [700 Hz]	*/a/$_{NT}$ [80 ms]	*/a/$_{T}$ [25 ms]	*/a/$_{T}$ [70 ms]	*/o/$_{T}$ [25 ms]	*/o/$_{T}$ [80 ms]	*/a/$_{NT}$ [470 Hz]	*/a/$_{NT}$ [25 ms]	*/a/$_{NT}$ [700 Hz]	*/a/$_{NT}$ [70 ms]	*/o/$_{T}$ [470 Hz]	*/o/$_{T}$ [70 ms]	*/a/$_{T}$ [700 Hz]	*/a/$_{T}$ [80 ms]
☜/.pa.ra.ˈdoks./[p***X***p***Y***d***Z***ks]									*	*	*	*	*	*		
/.po.ra.ˈdoks./[p***X***p***Y***d***Z***ks]	*!										*	*	*	*		

Selecting of candidates to represent in tableaus demonstrating production needs to be smart. All the combinations of our auditory features should be present, also the combinations that should not happen. Having two possible F1 values and three possible vowel durations makes 6 candidates for only one vowel. Then for three syllable word the number of candidates is 6ˆ3 = 216. We will try to reduce the number of candidates in a following way. First, we model the production of one-syllable word with the surface form /.ˈda./, this will repeat the tableau of the isolate phoneme /a/$_{T}$. Then, we move to the two-syllable surface form /.sa.ˈva./, fixating the optimally found sound for the /a/$_{T}$, so that we only need to find an optimal candidate for the first syllable /a/. The last step is to move to the three-syllable word /.ga.la.ˈva./, fixating the optimally found sounds for the second and third syllables which are /a/$_{1PT}$ and /a/$_{T}$ respectively. This approach is demonstrated in tableaus (18) – (20) for the words ending with /a/$_{T}$ and tableaus (21) – (23) for the surface forms ending with /o/$_{T}$.

(18) *Production of /.ˈda./*

/.ˈda./ ***X*** = [470Hz, 25ms] ***Y*** = [470Hz, 70ms] ***Z*** = [470Hz, 80ms] ***U*** = [700Hz, 25ms] ***V*** = [700Hz, 70ms] ***W*** = [700Hz, 80ms]	*[low, short]$_{ART}$	*/X/$_{2PT}$ [long]	*/a/$_{T}$ [470 Hz]	*/o/$_{T}$ [700 Hz]	*/a/$_{NT}$ [80 ms]	*/a/$_{T}$ [25 ms]	*/a/$_{T}$ [70 ms]	*/o/$_{T}$ [25 ms]	*/o/$_{T}$ [80 ms]	*/a/$_{NT}$ [470 Hz]	*/a/$_{NT}$ [25 ms]	*/a/$_{NT}$ [700 Hz]	*/a/$_{NT}$ [70 ms]	*/o/$_{T}$ [470 Hz]	*/o/$_{T}$ [70 ms]	*/a/$_{T}$ [700 Hz]	*/a/$_{T}$ [80 ms]
/.ˈda./[d***X***]			*!			*											
/.ˈda./[d***Y***]			*!				*										
/.ˈda./[d***Z***]			*!														*
/.ˈda./[d***U***]	*!					*										*	
/.ˈda./[d***V***]							*!									*	
☞/.ˈda./[d***W***]																*	*

(19) *Production of /.sa.ˈva./*

/.sa.ˈva./ ***X*** = [470Hz, 25ms] ***Y*** = [470Hz, 70ms] ***Z*** = [470Hz, 80ms] ***U*** = [700Hz, 25ms] ***V*** = [700Hz, 70ms] ***W*** = [700Hz, 80ms]	*[low, short]$_{\text{ART}}$	*/X/$_{\text{2PT}}$ [long]	*/a/$_{\text{T}}$ [470Hz]	*/o/$_{\text{T}}$ [700Hz]	*/a/$_{\text{NT}}$ [80ms]	*/a/$_{\text{T}}$ [25ms]	*/a/$_{\text{T}}$ [70ms]	*/o/$_{\text{T}}$ [25ms]	*/o/$_{\text{T}}$ [80ms]	*/a/$_{\text{NT}}$ [470Hz]	*/a/$_{\text{NT}}$ [25ms]	*/a/$_{\text{NT}}$ [700Hz]	*/a/$_{\text{NT}}$ [70ms]	*/o/$_{\text{T}}$ [470Hz]	*/o/$_{\text{T}}$ [70ms]	*/a/$_{\text{T}}$ [700Hz]	*/a/$_{\text{T}}$ [80ms]
/.sa.ˈva./[s***X***v***W***]										*!	*					*	*
/.sa.ˈva./[s***Y***v***W***]										*!			*			*	*
/.sa.ˈva./[s***Z***v***W***]					*!					*						*	*
/.sa.ˈva./[s***U***v***W***]	*!										*	*				*	*
☞/.sa.ˈva./[s***V***v***W***]												*	*			*	*
/.sa.ˈva./[s***W***v***W***]					*!							*				*	*

(20) *Production of /.ga.la.ˈva./*

/.ga.la.ˈva./ ***X*** = [470Hz, 25ms] ***Y*** = [470Hz, 70ms] ***Z*** = [470Hz, 80ms] ***U*** = [700Hz, 25ms] $\boxed{\boldsymbol{V} = [700Hz, 70ms]}$ $\boxed{\boldsymbol{W} = [700Hz, 80ms]}$	*[low, short]$_{ART}$	*/X/$_{2PT}$ [long]	*/a/$_{T}$ [470Hz]	*/o/$_{T}$ [700Hz]	*/a/$_{NT}$ [80ms]	*/a/$_{T}$ [25ms]	*/a/$_{T}$ [70ms]	*/o/$_{T}$ [25ms]	*/o/$_{T}$ [80ms]	*/a/$_{NT}$ [470Hz]	*/a/$_{NT}$ [25ms]	*/a/$_{NT}$ [700Hz]	*/a/$_{NT}$ [70ms]	*/o/$_{T}$ [470Hz]	*/o/$_{T}$ [70ms]	*/a/$_{T}$ [700Hz]	*/a/$_{T}$ [80ms]
☞/.ga.la.ˈva./[g***X***l$\boxed{\boldsymbol{V}}$v$\boxed{\boldsymbol{W}}$]										*	*	*	*			*	*
/.ga.la.ˈva./[g***Y***l$\boxed{\boldsymbol{V}}$v$\boxed{\boldsymbol{W}}$]		*!								*		*	**			*	*
/.ga.la.ˈva./[g***Z***l$\boxed{\boldsymbol{V}}$v$\boxed{\boldsymbol{W}}$]		*!			*					*		*	*			*	*
/.ga.la.ˈva./[g***U***l$\boxed{\boldsymbol{V}}$v$\boxed{\boldsymbol{W}}$]	*!										*	**	*			*	*
/.ga.la.ˈva./[g***V***l$\boxed{\boldsymbol{V}}$v$\boxed{\boldsymbol{W}}$]		*!										**	**			*	*
/.ga.la.ˈva./[g***W***l$\boxed{\boldsymbol{V}}$v$\boxed{\boldsymbol{W}}$]		*!			*							**	*			*	*

(21) *Production of /.ˈno./*

/.ˈno./ ***X*** = [470Hz, 25ms] ***Y*** = [470Hz, 70ms] ***Z*** = [470Hz, 80ms] ***U*** = [700Hz, 25ms] ***V*** = [700Hz, 70ms] ***W*** = [700Hz, 80ms]	*[low, short]$_{\text{ART}}$	*/X/$_{\text{2PT}}$ [long]	*/a/$_{\text{T}}$ [470Hz]	*/o/$_{\text{T}}$ [700Hz]	*/a/$_{\text{NT}}$ [80ms]	*/a/$_{\text{T}}$ [25ms]	*/a/$_{\text{T}}$ [70ms]	*/o/$_{\text{T}}$ [25ms]	*/o/$_{\text{T}}$ [80ms]	*/a/$_{\text{NT}}$ [470Hz]	*/a/$_{\text{NT}}$ [25ms]	*/a/$_{\text{NT}}$ [700Hz]	*/a/$_{\text{NT}}$ [70ms]	*/o/$_{\text{T}}$ [470Hz]	*/o/$_{\text{T}}$ [70ms]	*/a/$_{\text{T}}$ [700Hz]	*/a/$_{\text{T}}$ [80ms]
/.ˈno./[n***X***]								*!						*			
☞/.ˈno./[n***Y***]														*	*		
/.ˈno./[n***Z***]									*!					*			
/.ˈno./[n***U***]	*!			*				*									
/.ˈno./[n***V***]				*!											*		
/.ˈno./[n***W***]				*!					*								

(22) *Production of /.sa.ˈmo./*

/.sa.ˈmo./ ***X*** = [470Hz, 25ms] $\boxed{\boldsymbol{Y} = \text{[470Hz, 70ms]}}$ ***Z*** = [470Hz, 80ms] ***U*** = [700Hz, 25ms] ***V*** = [700Hz, 70ms] ***W*** = [700Hz, 80ms]	*[low, short]$_{ART}$	*/X/$_{2PT}$ [long]	*/a/$_{T}$ [470 Hz]	*/o/$_{T}$ [700 Hz]	*/a/$_{NT}$ [80 ms]	*/a/$_{T}$ [25 ms]	*/a/$_{T}$ [70 ms]	*/o/$_{T}$ [25 ms]	*/o/$_{T}$ [80 ms]	*/a/$_{NT}$ [470 Hz]	*/a/$_{NT}$ [25 ms]	*/a/$_{NT}$ [700 Hz]	*/a/$_{NT}$ [70 ms]	*/o/$_{T}$ [470 Hz]	*/o/$_{T}$ [70 ms]	*/a/$_{T}$ [700 Hz]	*/a/$_{T}$ [80 ms]
/.sa.ˈmo./[s***X***m$\boxed{\boldsymbol{Y}}$]										*!	*			*	*		
/.sa.ˈmo./[s***Y***m$\boxed{\boldsymbol{Y}}$]										*!			*	*	*		
/.sa.ˈmo./[s***Z***m$\boxed{\boldsymbol{Y}}$]					*!					*				*	*		
/.sa.ˈmo./[s***U***m$\boxed{\boldsymbol{Y}}$]	*!										*	*		*	*		
☞/.sa.ˈmo./[s***V***m$\boxed{\boldsymbol{Y}}$]												*	*	*	*		
/.sa.ˈmo./[s***W***m$\boxed{\boldsymbol{Y}}$]					*!							*		*	*		

(23) *Production of /.pa.ra.ˈdoks./*

/.pa.ra.ˈdoks./ ***X*** = [470Hz, 25ms] $\boxed{\textbf{\textit{Y}} = \text{[470Hz, 70ms]}}$ ***Z*** = [470Hz, 80ms] ***U*** = [700Hz, 25ms] $\boxed{\textbf{\textit{V}} = \text{[700Hz, 70ms]}}$ ***W*** = [700Hz, 80ms]	*[low, short]$_{\text{ART}}$	*/X/ 2PT [long]	*/a/ T [470 Hz]	*/o/ T [700 Hz]	*/a/ NT [80 ms]	*/a/ T [25 ms]	*/a/ T [70 ms]	*/o/ T [25 ms]	*/o/ T [80 ms]	*/a/ NT [470 Hz]	*/a/ NT [25 ms]	*/a/ NT [700 Hz]	*/a/ NT [70 ms]	*/o/ T [470 Hz]	*/o/ T [70 ms]	*/a/ T [700 Hz]	*/a/ T [80 ms]
☞/.pa.ra.ˈdoks./[p***X***r$\boxed{\textbf{\textit{V}}}d\boxed{\textbf{\textit{Y}}}$ks]										*	*	*	*	*	*		
/.pa.ra.ˈdoks./[p***Y***r$\boxed{\textbf{\textit{V}}}d\boxed{\textbf{\textit{Y}}}$ks]		*!								*		*	**	*	*		
/.pa.ra.ˈdoks./[p***Z***r$\boxed{\textbf{\textit{V}}}d\boxed{\textbf{\textit{Y}}}$ks]		*!			*					*		*	*	*	*		
/.pa.ra.ˈdoks./[p***U***r$\boxed{\textbf{\textit{V}}}d\boxed{\textbf{\textit{Y}}}$ks]	*!										*	**	*	*	*		
/.pa.ra.ˈdoks./[p***V***r$\boxed{\textbf{\textit{V}}}d\boxed{\textbf{\textit{Y}}}$ks]		*!										**	**	*	*		
/.pa.ra.ˈdoks./[p***W***r$\boxed{\textbf{\textit{V}}}d\boxed{\textbf{\textit{Y}}}$ks]		*!			*							**	*	*	*		

5. Phonology-semantics interface

As it was demonstrated in section 2, having a semantic level in our grammar model can facilitate choosing the proper underlying form during the comprehension process. This process is modelled for the surface form /.sa.ˈva./ in the tableau (24). Between the surface and underlying level there are only faithfulness constraints, in this case IDENT-IO (V_T) (which prevents the change of the tonic vowel) and IDENT-IO (V_{NT}) (which prevents the change of the non-tonic vowel), providing for the choice of the underlying forms |sava|. But this underlying form does not exist, meaning that it is not connected to any morpheme. Existing underlying form is |sova| (which is connected to the morpheme <owl>). This can be fixed using a lexical constraint *< >|X|, which prevent an underlying form that is not connected to any morpheme.

(24) *Word recognition: adding the lexical constraint*

/.sa.ˈva./	*< >|X|	*/o/$_{NT}$	IDENT-IO (V_T)	IDENT-IO (V)
☜ <owl>|sova|/.sa.ˈva./				*
< >|sava|/.sa.ˈva./	*!			

What is worth mentioning is that tableau (3) also includes structural constraint */o/$_{NS}$ which we already used in the perception tableaus (4) – (7) and (14) – (17). Obviously, it will not play any role during word recognition, because it sets restrictions on the surface form, which in this case is an input form. On the contrary, it will play a role in the production process, which is modelled in the tableau (25), whereas the lexical constraint (*< >|X|) will not restrict anything in production, because it restricts only the input (underlying) form.

(25) *Production*

<owl>|sova|	*< >|M|	*/o/$_{NT}$	IDENT-IO (V_T)	IDENT-IO (V)
<owl>|sova|/.so.ˈva./		*!		
☞ <owl>|sova|/.sa.ˈva./				*

6. Full bidirectional four-level OT model for Akanje

The last step is to construct the full bidirectional OT model for Akanje, by connecting the two "submodels" together: the phonological-phonetic model created in section 4 and the phonological-semantic model described in section 5. Picture 2 schematically shows the bidirectional processing of the word <head>|golova|.

<head>

↓↑

|golova|

↓↑

/.ga.la.ˈva/

↓↑

[g	470Hz 25ms	l	700Hz 70ms	v	700Hz 80ms	]

Picture 2. Bidirectional processing using BiPhon model

Tableaus (26) – (29) contain the examples of the full analysis of two example words: <head>|golova|, and <paradox>|paradoks|, first for comprehension and then for production. These tableaus are not meant to be comprehensive like the tableaus in the previous sections, but rather used for demonstration of the full model working. It is possible, that some reranking is needed in the full model, but the small scale of the current research does not allow to include the necessary for it analysis here.

(26) *Comprehension of [g**X**l**Y**v**Z**], where **X** = [470Hz, 25ms], **Y** = [700Hz, 70ms], **Z** = [700Hz, 80ms]*

[g**X**l**Y**v**Z**] **X** = [470Hz, 25ms] **Y** = [700Hz, 70ms] **Z** = [700Hz, 80ms]	*< > |M|	/*o/$_{NT}$	*/a/$_{T}$ [470 Hz]	*/o/$_{T}$ [700 Hz]	*/a/$_{NT}$ [80 ms]	*/a/$_{T}$ [25 ms]	*/a/$_{T}$ [70 ms]	*/o/$_{T}$ [25 ms]	*/o/$_{T}$ [80 ms]	IDENT-IO (V_T)	*/a/$_{NT}$ [470 Hz]	*/a/$_{NT}$ [25 ms]	*/a/$_{NT}$ [700 Hz]	*/a/$_{NT}$ [70 ms]	*/o/$_{T}$ [470 Hz]	*/o/$_{T}$ [70 ms]	*/a/$_{T}$ [700 Hz]	*/a/$_{T}$ [80 ms]
☜ <head>|golova| /ga.la.ˈva./[g**X**l**Y**v**Z**]											*	*	*	*			*	*
<head>|golova| /go.la.ˈva./[g**X**l**Y**v**Z**]		*!											*	*			*	*
< >|galova| /ga.ˈlo.va./[g**X**l**Y**v**Z**]	*!			*	*						*	*	*			*		

(27) *Comprehension of [p**X**r**Y**d**Z**ks], where **X** = [470Hz, 25ms], **Y** = [700Hz, 70ms], **Z** = [700Hz, 80ms]*

[p***X***r***Y***d***Z***ks] ***X*** = [470Hz, 25ms] ***Y*** = [700Hz, 70ms] ***Z*** = [470Hz, 70ms]	*< > |M|	/*o/ $_{NT}$	*/a/ $_{T}$ [470 Hz]	*/o/ $_{T}$ [700 Hz]	*/a/ $_{NT}$ [80 ms]	*/a/ $_{T}$ [25 ms]	*/a/ $_{T}$ [70 ms]	*/o/ $_{T}$ [25 ms]	*/o/ $_{T}$ [80 ms]	IDENT-IO (V_T)	*/a/ $_{NT}$ [470 Hz]	*/a/ $_{NT}$ [25 ms]	*/a/ $_{NT}$ [700 Hz]	*/a/ $_{NT}$ [70 ms]	*/o/ $_{T}$ [470 Hz]	*/o/ $_{T}$ [70 ms]	*/a/ $_{T}$ [700 Hz]	*/a/ $_{T}$ [80 ms]
☜ <paradox> |paradox| /.pa.ra.ˈdoks./ [p***X***p***Y***d***Z***ks]											*	*	*	*	*	*		
<paradox> |paradox| /.po.ra.ˈdoks./ [p***X***p***Y***d***Z***ks]		*!											*	*	*	*		
< > |paradax| /.ˈpa.ra.daks./ [p***X***p***Y***d***Z***ks]	*!		*			*							**	**				

(28) *Production of* <*head*>|*golova*|

<head>|golova| ***X*** = [470Hz, 25ms] ***Y*** = [470Hz, 70ms] ***Z*** = [470Hz, 80ms] ***U*** = [700Hz, 25ms] ***V*** = [700Hz, 70ms] ***W*** = [700Hz, 80ms]	*<>|M|	/*o/$_{NT}$	*[low, short]$_{ART}$	*/X/$_{2PT}$ [long]	*/a/$_T$[470Hz]	*/o/$_T$[700Hz]	*/a/$_{NT}$[80ms]	*/a/$_T$[25ms]	*/a/$_T$[70ms]	*/o/$_T$[25ms]	*/o/$_T$[80ms]	IDENT-IO (V$_T$)	*/a/$_{NT}$[470Hz]	*/a/$_{NT}$[25ms]	*/a/$_{NT}$[700Hz]	*/a/$_{NT}$[70ms]	*/o/$_T$[470Hz]	*/o/$_T$[70ms]	*/a/$_T$[700Hz]	*/a/$_T$[80ms]
<head>|golova| /.go.lo.ˈva./[g***X***l***Y***v***Z***]		**!			*															*
<head>|golova| /.ga.la.ˈva./[g***U***l***V***v***W***]			*!											*	**	*			*	*
<head>|golova| /.ga.la.ˈvo./[g***X***l***V***v***Y***]												*!	*	*	*	*	*	*		
☞<head>|golova| /.ga.la.ˈva./[g***X***l***V***v***W***]													*	*	*	*			*	*
<head>|golova| /.ga.la.ˈva./[g***V***l***V***v***W***]				*!											**	**				

(29) *Production of <paradox> |paradoks|*

<paradox> |paradoks| ***X*** = [470Hz, 25ms] ***Y*** = [470Hz, 70ms] ***Z*** = [470Hz, 80ms] ***U*** = [700Hz, 25ms] ***V*** = [700Hz, 70ms] ***W*** = [700Hz, 80ms]	*<>|M|	/*o/$_{NT}$	*[low, short]$_{ART}$	*/X/$_{2PT}$ [long]	*/a/$_T$[470Hz]	*/o/$_T$[700Hz]	*/a/$_{NT}$[80ms]	*/a/$_T$[25ms]	*/a/$_T$[70ms]	*/o/$_T$[25ms]	*/o/$_T$[80ms]	IDENT-IO (V$_T$)	*/a/$_{NT}$[470Hz]	*/a/$_{NT}$[25ms]	*/a/$_{NT}$[700Hz]	*/a/$_{NT}$[70ms]	*/o/$_T$[470Hz]	*/o/$_T$[70ms]	*/a/$_T$[700Hz]	*/a/$_T$[80ms]
☞ <paradox> |paradoks| /.pa.ra.ˈdoks./[g***X***l***V***v***Y***]													*	*	*	*	*	*		
<paradox> |paradoks| /.pa.ra.ˈdaks./[g***X***l***V***v***W***]												*!	*	*	*	*			*	*
<paradox> |paradoks| /.ˈpo.ra.daks./[g***Z***l***V***v***Y***]											*!	*			**	**	*			
<paradox> |paradoks| /.pa.ra.ˈdoks./[g***U***l***Y***v***W***]			*!			*					*		*	*	*	*				
<paradox> |paradoks| /.pa.ro.ˈdaks./[g***V***l***V***v***W***]		*!										*			*	*			*	*

7. Conclusion

This paper aimed to exercise using BiPhon full grammar model for analysing comprehension and production of the Contemporary Standard Russian Akanje. Although there were several simplifications made in my analysis, I think that BiPhon model proved to be very helpful. One of the simplifications that leaves the subject open for additional research is leaving the analysis of Akanje in palatalized contexts outside of the scope of the current study. Another limitation of this study is that it only examines first and second pretonic vowels, leaving out posttonic vowels and vowels that are farther apart from the stressed syllable than only two syllables. Particularly interesting cases for further analysis are what Barnes calls “exceptional phonological contexts” (Barnes, 2007). This group of contexts includes absolute phrase-final position, different hiatus configurations, and absolute word-initial position.

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