

# The acquisition and evolution of faithfulness rankings

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## 1. What this paper is going to show

This paper will derive observed universal rankings of faithfulness constraints from biases in acquisition that result from (1) frequency differences in the input and (2) imperfections in the transmission channel:

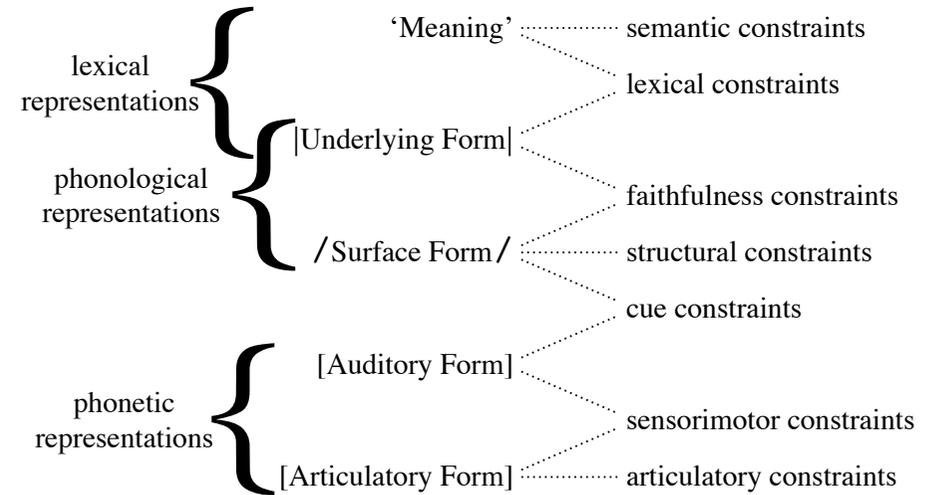
**1.1.** The computer simulations of the present paper show that in **acquisition**, the child's constraint rankings will *more or less* end up where they yield a grammar that generates the parents' language. But the ranking will diverge a bit, as a result of the above-mentioned frequency differences and imperfections.

**1.2.** Even if the parents' language has all faithfulness constraints ranked at the same height, their children will gradually rank them according to one of the **universal rankings** that have been proposed in the literature (e.g. *licensing by cue*, *positional faithfulness*, *probabilistic faithfulness*, *markedness as specification strength*).

**1.3.** All these rankings are therefore caused **automatically** by imperfections in the transmission channel in combination with a simple learning algorithm. None of the causes proposed before (all of which were based on the assumption that speakers have some sort of explicit or implicit linguistic or extralinguistic knowledge) are needed.

## 2. The required minimal bidirectional grammar model

**2.1.** These five **representations** are based on Boersma (1998, 2005), but feature an additional separation within the lexicon between the *signifié* and the *signifiant* (Saussure 1916), the two sides of the form-meaning pair (see also Diana Apoussidou's talk, this conference):



## 2.2. Seven constraint types: where do they come from?

The **structural** and **faithfulness** constraints are based on Prince & Smolensky (1993) and McCarthy & Prince (1995), the **articulatory** constraints on Jun (1995), Kirchner (1998), and Boersma (1998).

The **cue** constraints (the interface between phonology and phonetics) are based on Boersma (1998) and Escudero & Boersma (2003). The term was coined by Boersma (2005) and Escudero (2005).

The **lexical** and **semantic** constraints are based on Boersma (2001), Escudero (2005), and Apoussidou (this conference), who use them for choosing between underlying [rat] and [rad], [tʃeka] and [tʃika], or [θalas] and [θálas]. OT semanticists use similar form-meaning constraints for choosing between *kill* and *cause to die* (Blutner 2000), or between *him* and *himself* (Wilson 2001).

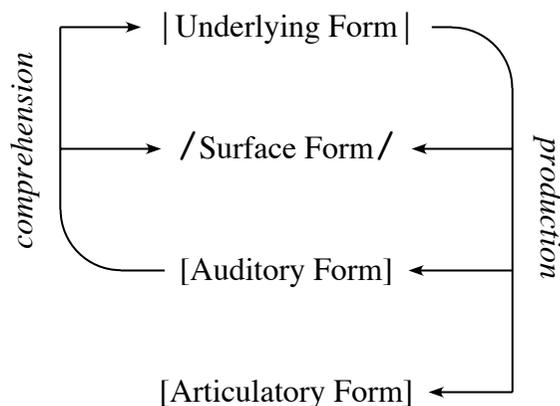
### 2.3. Simplification, just for this talk

For purposes of simplicity (but see the Discussion section), I will collapse Meaning and Underlying Form into one, basically assuming that there is a 1-to-1 relationship between the two (i.e. that the lexical constraints are ‘perfect’).

Also, I will usually collapse Auditory and Articulatory Form into one ‘phonetic form’, assuming that sensorimotor knowledge is ‘perfect’.

### 2.4. Bidirectional parallel processing

For this talk I simply assume that both comprehension and production are parallel processes (i.e. they do not consist of sequential modules):



### 2.5. Case: place assimilation

The forms that have to be evaluated in comprehension as well as in production are triplets of Underlying Form (e.g. |an+pa|, which includes a morpheme boundary), a discrete phonological Surface Form (e.g. /ampa/), and a phonetically detailed auditory/articulatory form (e.g. [aNpa], where [N] stands for a reduced coronal nasal). For instance, the triplet |an+pa| /ampa/ [ampa] shows full ‘phonological’ place assimilation, whereas the triplet |an+pa| /anpa/ [ampa] shows full ‘phonetic’ place assimilation.

## 3. Learning place assimilation from your parents

**3.1. The primary language data** for the beginning infant consists of auditory forms and a semantic/pragmatic context. For this talk, however, simulations begin in a later stage, namely when the child already has correct lexical form-meaning pairs. The primary language data consist, then, of **pairs of underlying form and auditory form**, e.g. |an+pa| [ampa].

### 3.2. Language environment for coronal nasal place assimilation.

For the simulations in chapter 3, I assume a Dutch or Catalan type of place assimilation: underlying |an+pa| is pronounced (by the parents) as [ampa] in 80% of the cases, and as [anpa] in 20% of the cases, while underlying |at+ma| is pronounced as [atma] in 99% of the cases, and as [apma] in 1% of the cases. Underlying forms with labial codas are pronounced fully labially. The full **distribution** of underlying–auditory pairs is then:

an+pa  [anpa]	20	am+ta  [amta]	100
an+pa  [ampa]	80	am+ta  [anta]	0
at+ma  [atma]	99	ap+na  [apna]	100
at+ma  [apma]	1	ap+na  [atna]	0

**Question 1:** will the simulated learners mimic these distributions?

**3.3. The learning task** is to find the intermediate forms, namely the **surface forms**. Like other surface structures (e.g. foot structure), these forms are inaudible and are not part of the primary language data; they have to be constructed by the learner. For the learning pair |an+pa|[ampa], the child probably constructs either /ampa/ or /anpa/.

**Question 2:** what will the simulated learners’ surface forms look like?

**3.4. The learning algorithm** is a simple *bidirectional optimization*, which is illustrated in the tableau below, where an illustrative example grammar (different from the ones used in my simulations) contains one faithfulness constraint, one unlikely structural constraint, four cue constraints, and three articulatory constraint.

The tableau illustrates the learning of the pair |an+pa| [ampa] and contains all candidates that contain either |an+pa| or [ampa] (or both). The numbers above the tableau show the continuous ‘disharmonies’ (ranking values + evaluation noise) of every constraint (I assume Stochastic OT; see Boersma 1997 and Boersma & Hayes 2001).

The candidate that the learner will regard as ‘**correct**’ (✓) is the one that is the most optimal of all the candidates that contain both |an+pa| and [ampa]; the ‘**forward**’ **winner** (☞) is the best of all the candidates that contain |an+pa|; and the ‘**backward**’ **winner** (☜) is the best of all the candidates that contain [ampa].

The tableau shows how the constraints will **move** if one or both of the winners differs from the ‘correct’ candidate. All constraints violated in an ‘incorrect’ winner will move up the continuous ranking scale, and all constraints violated in the ‘correct’ form will move down (by two steps in the tableau, because the form is compared to two other forms).

	101.7	101.0	100.0	99.9	99.6	98.6	98.3	97.9	96.9
an+pa  [ampa]	*/p/[t]	*/t/[p]	IDENT	*/n/[m]	*/m/[n]	*[lip-tongue synchronization]	*[lip gesture]	*/mp/	*[tongue gesture]
✓  an+pa  /anpa/[ampa]				*→→			*→→		
☞  an+pa  /anpa/[anpa]						←*	←*		←*
an+pa  /ampa/[ampa]			*				*	*	
an+pa  /ampa/[anpa]			*		*	*	*	*	*
am+pa  /anpa/[ampa]			*	*			*		
☜  am+pa  /ampa/[ampa]							←*	←*	

### 3.5. Simplification number 5

After the previous four simplifications (collapsing word-meaning pairs, collapsing auditory and articulatory forms, assuming parallel comprehension, and assuming the single learning algorithm of bidirectional optimization), there is a fifth simplification.

This simplification, not implemented in the tableau below, is that production does not neutralize, i.e. the underlying form can always be recovered from the auditory form (or from the surface form). For instance, there will exist an underlying form |an+pa|, but there will not exist an underlying form |am+pa| such as appears in the tableau below.

With this simplification, bidirectional optimization reduces to ‘forward’ optimization (no “☞” in the learning tableaux), i.e. robust perception with virtual production (Apoussidou & Boersma 2004). This is fully comparable to Tesar & Smolensky’s (1998, 2000) ‘robust interpretive parsing with constraint demotion’, except that the mappings from Surface Form to Auditory Form (Tesar & Smolensky’s Overt Form) and from Surface Form to Underlying Form are in the present paper no longer trivial but handled by the grammar, i.e. by the rankings of cue constraints and faithfulness constraints, respectively.

### 3.6. Simulation: a single constraint for place faithfulness

The tableau below shows simulation results for a learner with four cue constraints (the one on top means “a phonological element /p/ does not correspond to a phonetic [t]”), one articulatory constraint LAZY (violated by the articulatory distance between the coda and the onset, in some arbitrary units), and a single faithfulness constraint IDENTPLACE. The learner is restricted to the four underlying forms shown. After 400,000 learning pairs drawn from the distribution in §3.2, this learner

ends up with the ranking values above the tableau (training scheme: 100,000 learning pairs each at plasticities of 1, 0.1, 0.01, and 0.001; the strength of the evaluation noise is always 2.0). The numbers at the right are output frequencies given the underlying form |an+pa| (or |at+ma|), computed by running it through the stochastic grammar 100,000 times.

**Answers:** with these constraints and candidates, learners replicate their parents’ distribution; and with a single IDENTPLACE, the surface form is always /ampa/, i.e., assimilation of [n] must be entirely phonetic.

	105.9	105.3	102.6	100.9	93.9	91.5	
	*[t] /p/	*[n] /m/	IDENTPLACE	*[p] /t/	LAZY	*[m] /n/	
☞  an+pa  /anpa/[ampa]						*	an+pa  : 80%
an+pa  /anpa/[anpa]					*!***		20%
an+pa  /ampa/[ampa]			*!				0%
an+pa  /ampa/[anpa]		*!	*		***		0%
am+ta  /anta/[amta]			*!		***	*	
am+ta  /anta/[anta]			*!				
am+ta  /amta/[amta]					*!***		
am+ta  /amta/[anta]		*!					at+ma  : 0.7%
at+ma  /atma/[apma]				*!			0.7%
at+ma  /atma/[atma]					*!***		99.2%
at+ma  /apma/[apma]			*!				0.1%
at+ma  /apma/[atma]	*!		*		***		0%
ap+na  /atna/[apna]			*!	*	***		
ap+na  /atna/[atna]			*!				
ap+na  /apna/[apna]					*!***		
ap+na  /apna/[atna]	*!						

### 3.7. Simulation: more phonology by more granular faithfulness

To achieve more ‘phonological’ solutions, this tableau implements a possibility inspired by Jun (1995), namely to have two separate faithfulness constraints for the two values of the place feature, namely IDENTPLACE(|labial|) and IDENTPLACE(|coronal|), and to have two separate faithfulness constraints for the two different manners, namely IDENTPLACE(nasal) and IDENTPLACE(plosive).

**Answers:** with these constraints and candidates, the learners replicate their parents’ distribution. The 81% [ampa] forms are now distributed more or less evenly between ‘phonetic’ assimilation (candidate 1, /anpa/) and ‘phonological’ assimilation (candidate 3, /ampa/).

**Note:** the pointing finger at the candidate |an+pa|/anpa/[ampa] just means that this is the most harmonic triplet in the learner’s language.

	107.0	106.9	106.9	102.3	101.7	94.8	93.8	93.5	88.6	
	*[n] /m/	*[t] /p/	IDPL ( lab )	*[p] /t/	IDPL (plos)	LAZY	IDPL (nas)	*[m] /n/	IDPL ( cor )	
  an+pa  /anpa/[ampa]								*		an+pa  : 45%
an+pa  /anpa/[anpa]						*!***				19%
an+pa  /ampa/[ampa]							*!		*	36%
an+pa  /ampa/[anpa]	*!					***	*		*	0%
am+ta  /anta/[amta]			*!			***	*	*		
am+ta  /anta/[anta]			*!				*			
am+ta  /amta/[amta]						*!***				
am+ta  /amta/[anta]	*!									at+ma  :
at+ma  /atma/[apma]				*!						0.4%
at+ma  /atma/[atma]						*!***				98.9%
at+ma  /apma/[apma]					*!				*	0.7%
at+ma  /apma/[atma]		*!			*	***			*	0%
ap+na  /atna/[apna]			*!	*	*	***				
ap+na  /atna/[atna]			*!		*					
ap+na  /apna/[apna]						*!***				
ap+na  /apna/[atna]		*!								

### 3.8. Simulation: variation between learners

This simulation follows Boersma (1998: 217) in having the faithfulness constraints “IDPL” (= IDENTPLACE) specific to each of the four underlying segments. The cue constraints are still universal (no \*[m]/m/) and discrete (no \*[M]/m/). This means that the cue constraints and the faithfulness constraints have the exact same degree of granularity (four) and the exact same bias (towards “identity”).

Perhaps not surprisingly, \*[m]/n/ and IDENTPLACE(n) end up being ranked equally high. For the combination of underlying |an+pa| and phonetic [ampa], the surface form will therefore be /anpa/ half of the time (‘phonetic assimilation’) and /ampa/ half of the time (‘phonological assimilation’). **This simulated learner** appears to have the same trouble localizing assimilation as the linguistic community has as a whole.

	105.9	105.6	105.5	104.9	100.4	100.4	93.2	92.1	92.0	
	IDPL ( m )	*[t] /p/	*[n] /m/	IDPL ( p )	IDPL ( t )	*[p] /t/	LAZY	*[m] /n/	IDPL ( n )	
an+pa  / anpa / [ampa]								*!		an+pa  : 40%
an+pa  / anpa / [anpa]							*!***			20%
☞  an+pa  / ampa / [ampa]									*	40%
an+pa  / ampa / [anpa]			*!				***		*	0%
am+ta  / anta / [amta]	*!						***	*		
am+ta  / anta / [anta]	*!									
am+ta  / amta / [amta]							*!***			
am+ta  / amta / [anta]			*!							at+ma  :
at+ma  / atma / [apma]						*!				0.5%
at+ma  / atma / [atma]							*!***			99%
at+ma  / apma / [apma]					*!					0.5%
at+ma  / apma / [atma]		*!			*		***			0%
ap+na  / atna / [apna]				*!		*	***			
ap+na  / atna / [atna]				*!						
ap+na  / apna / [apna]							*!***			
ap+na  / apna / [atna]		*!								

But some learners end up with a grammar that does ‘phonetic assimilation’) all of the time, at least for the nasals. The phonetic forms still match the input distribution, though. (for the plosives, it’s still half-half)

Differently from the previous learner, **this simulated learner** appears to have made the same choice as a part of the linguistic community.

	105.3	105.0	103.9	103.4	101.9	99.8	98.9	92.0	89.7	
	IDPL ( p )	*[n] /m/	*[t] /p/	IDPL ( m )	IDPL ( n )	*[p] /t/	IDPL ( t )	LAZY	*[m] /n/	an+pa  :
☞  an+pa  /anpa/[ampa]									*	80%
an+pa  /anpa/[anpa]								*!***		20%
an+pa  /ampa/[ampa]					*!					0%
an+pa  /ampa/[anpa]		*!			*			***		0%
am+ta  /anta/[amta]				*!				***	*	
am+ta  /anta/[anta]				*!						
am+ta  /amta/[amta]								*!***		
am+ta  /amta/[anta]		*!								
at+ma  /atma/[apma]						*!				
at+ma  /atma/[atma]								*!***		
at+ma  /apma/[apma]							*!			
at+ma  /apma/[atma]			*!				*	***		
ap+na  /atna/[apna]	*!					*		***		
ap+na  /atna/[atna]	*!									
ap+na  /apna/[apna]								*!***		
ap+na  /apna/[atna]			*!							

### 3.9. Simulation: auditory cues are arbitrary

If we regard auditory cues as arbitrarily related to phonological elements, then we have to include cue constraints like \*[m]/m/, because the sound [m] has no a priori relation with the phoneme /m/. In the simulation, something goes out of hand: LAZY shoots off beyond the bottom of the hierarchy. This is because \*[n]/n/ will now outrule the ‘all-ampa’ candidate.

**Answers.** These learners do *not* match their parents’ distribution.

To allow the presence of arbitrary constraints (including seemingly contrary ones like \*[n]/n/), we will need some sanity data such as |in+ti| [inti]. (note: such sanity data could also come from the onset of the second syllable in each form here, but I assume that all the constraints mentioned here are specific to the coda, so that /apna/[apna] does not violate \*/n/[n])

	106.4	104.5	104.4	103.2	101.5	101.4	98.6	98.5	97.4	94.8	51.6	51.6	-5558.6	
	IDPL (p)	*[p] /t/	IDPL (t)	*[t] /p/	*[n] /m/	*[n] /n/	*[m] /n/	*[m] /m/	*[t] /t/	*[p] /p/	IDPL (n)	IDPL (m)	LAZY	an+pa  :
an+pa  /ampa/[ampa]							*!							45%
an+pa  /anpa/[anpa]						*!							***	5%
an+pa  /ampa/[ampa]								*!			*			45%
an+pa  /ampa/[anpa]					*!						*		***	5%
am+ta  /anta/[amta]							*!					*	***	
am+ta  /anta/[anta]						*!						*		
am+ta  /amta/[amta]								*!					***	
am+ta  /amta/[anta]					*!									
at+ma  /atma/[apma]		*!												
at+ma  /atma/[atma]									*!					***
at+ma  /apma/[apma]			*!							*				
at+ma  /apma/[atma]			*!	*										***
ap+na  /atna/[apna]	*!	*												***
ap+na  /atna/[atna]	*!								*					
☞  ap+na  /apna/[apna]										*				***
ap+na  /apna/[atna]				*!										

### 3.10. Simulation: more underlying forms, for more reliable learning

When an equal number of non-assimilating forms (exemplified by forms with the vowel /i/) is included (all faithful and with perfect cues), we again get an 80% assimilation for |n|, and it is again due to an equal ranking of \*[m]/n/ and IDENTPLACE(|n|) just below LAZY. A 1% assimilation for |t| is again due to an equal ranking of \*[p]/t/ and IDENTPLACE(|t|) 3 noise strengths above LAZY.

**Conclusion:** it's important to have sufficiently broad primary language data.

	122.6	122.6	122.1	121.7	118.6	118.5	111.1	110.4	109.9	101.5	85.6	73.8	65.6
	IDPL ( p )	*[n] /m/	*[t] /p/	IDPL ( m )	*[p] /t/	IDPL ( t )	LAZY	*[m] /n/	IDPL ( n )	*[n] /n/	*[t] /t/	*[p] /p/	*[m] /m/
an+pa   /anpa/[ampa]								*!					
an+pa   /anpa/[anpa]							*!***			*			
an+pa   /ampa/[ampa]									*!				*
an+pa   /ampa/[anpa]		*!					***		*				
am+ta   /anta/[amta]				*!			***	*					
am+ta   /anta/[anta]				*!						*			
am+ta   /amta/[amta]							*!***						*
am+ta   /amta/[anta]		*!											
at+ma   /atma/[apma]					*!								
at+ma   /atma/[atma]							*!***				*		
at+ma   /apma/[apma]						*!						*	
at+ma   /apma/[atma]			*!			*	***						
ap+na   /atna/[apna]	*!				*		***						
ap+na   /atna/[atna]	*!										*		
ap+na   /apna/[apna]							*!***					*	
ap+na   /apna/[atna]			*!										
☞   im+pi   /impi/[impi]													*
im+pi   /impi/[inpi]		*!					***						
im+pi   /inpi/[impi]				*!				*					
im+pi   /inpi/[inpi]				*!			***			*			
in+ti   /inti/[imti]							*!***	*					
in+ti   /inti/[inti]										*!			
in+ti   /imti/[imti]							*!***		*				*
in+ti   /imti/[inti]		*!							*				
ip+mi   /ipmi/[ipmi]												*!	
ip+mi   /ipmi/[itmi]			*!				***						
ip+mi   /itmi/[ipmi]	*!				*								
ip+mi   /itmi/[itmi]	*!						***				*		
it+ni   /itni/[ipni]					*!		***						
it+ni   /itni/[itni]											*!		
it+ni   /ipni/[ipni]						*!	***					*	
it+ni   /ipni/[itni]			*!			*							

**3.11. Remaining problem:** real auditory cue values are not unary, not binary, but multi-valued.

## 4. Learning place assimilation on your own

The ranking of faithfulness constraints has been observed to depend on two major circumstances:

(1) **environment**: *positional faithfulness* (Beckman 1998), *licensing by cues* (Steriade 1995), *probabilistic faithfulness* (Boersma 1998, 2003).

(2) **relative frequency**: *markedness by faithfulness* (Boersma 1998:180–184).

I will show that both types of universal rankings emerge automatically as a side effect of learning. No innate ranking, no extralinguistic knowledge, and no linguistic computation have to be proposed.

### 4.1. Generation 1: perfectly faithful, and with a frequency bias

Suppose that Generation 1 has neither of the above-mentioned universal rankings. In fact, they have no faithfulness violations and also implement the surface forms with perfect articulations. They do have a *coronal frequency bias* of 2.0, i.e. underlying coronal codas occur twice as often as underlying labial codas. Their production distribution can therefore be described as follows:

at+ma  /atma/ [atma]	200	ip+mi  /ipmi/ [ipmi]	100
ap+na  /apna/ [apna]	100	it+ni  /itni/ [itni]	200
an+pa  /anpa/ [anpa]	200	im+pi  /impi/ [impi]	100
am+ta  /amta/ [amta]	100	in+ti  /inti/ [inti]	200

### 4.2. A continuum of auditory cue values

Real auditory possibilities are not just [n] and [m], but a large number of values along an auditory place continuum, most likely of a spectral nature. For this talk I simply assume that the continuum for nasals from labial to coronal is [m] – [M] – [N] – [n], where [M] and [N] are a ‘reduced’ [m] and [n], respectively. Likewise, the continuum for plosives is [p] – [P] – [T] – [t].

### 4.3. Input for Generation 2: transmission noise

The perfect phonetic output of Generation 1 (§4.1) is changed by the imperfections of the transmission channel (background noises produced by wind, other speakers, and blood flow). For the present simulation, I simplifyingly assume that the transmission noise does not affect the auditory cues of the onset consonants, which are therefore always the ‘perfect’ [m], [n], [p], and [t]. I also assume that it does not affect the codas that are underlyingly homorganic to the following onsets.

So the transmission noise affects the heterorganic codas only. Importantly, the relative influence of ‘noise’ is larger if the ‘signal’ (the auditory cues for place) is weaker, so the auditory place values in the environment are more variable for **nasals** than for **plosives**.

The primary language data (auditory + underlying form) for a learner of generation 2 can thus be described by the following distribution:

at+ma  [apma]	2	ip+mi  [ipmi]	100
at+ma  [aPma]	16	ip+mi  [iPmi]	0
at+ma  [aTma]	68	ip+mi  [iTmi]	0
at+ma  [atma]	114	ip+mi  [itmi]	0
ap+na  [apna]	57	it+ni  [ipni]	0
ap+na  [aPna]	34	it+ni  [iPni]	0
ap+na  [aTna]	8	it+ni  [iTni]	0
ap+na  [atna]	1	it+ni  [itni]	200
an+pa  [ampa]	22	im+pi  [impi]	100
an+pa  [aMpa]	44	im+pi  [iMpi]	0
an+pa  [aNpa]	62	im+pi  [iNpi]	0
an+pa  [anpa]	72	im+pi  [inpi]	0
am+ta  [amta]	36	in+ti  [imti]	0
am+ta  [aMta]	31	in+ti  [iMti]	0
am+ta  [aNta]	22	in+ti  [iNti]	0
am+ta  [anta]	11	in+ti  [inti]	200

#### 4.4. Simulation settings

One thousand virtual learners had four faithfulness constraints, 16 cue constraints, and one articulatory constraint, and started with all 21 constraints ranked at 100.0. Each of them was subsequently fed with 400,000 underlying–auditory form pairs randomly selected from the distribution in §4.3, with the same decreasing plasticity as in the previous simulations and the same evaluation noise. The learning algorithm was bidirectional and parallel again, which in this case (since there are no homophones in the lexicon) boils down to unidirectional learning from underlying form to auditory form, i.e. the usual *robust interpretive parsing with virtual production*.

#### 4.5. Simulation results

The tableau below shows the ‘median learner’, i.e. a learner whose each constraint ranking is the median of the rankings for 1000 learners.

The percentages after the tableau give the probabilities of each of the eight possible outputs, measured by running |an+pa| through the median learner’s grammar 100,000 times (if we instead run |an+pa| through every learner’s grammar 100 times, we get very similar results).

It can be seen that the learners have a special bias towards the least-assimilating form [anpa] (43.4%, whereas only 36% in the input) and towards the most-assimilating form [ampa] (28.6% instead of 11%).

	108.2	107.5	104.5	103.7	103.2	103.2	102.9	102.3	101.9	101.4	100.0	99.6	99.6	99.2	98.6	98.5	98.0	97.3	96.4	91.0	90.4	
an+pa	*[p] /t/	*[t] /p/	*[m] /n/	IDPL ( p )	*[n] /m/	*[P] /t/	IDPL ( t )	*[T] /p/	IDPL ( m )	*[M] /n/	IDPL ( n )	*[N] /m/	*[N] /n/	*[T] /t/	LAZY	*[P] /p/	*[M] /m/	*[m] /m/	*[n] /n/	*[p] /p/	*[t] /t/	
an+pa  /anpa/[ampa]			*!																			0.7%
an+pa  /anpa/[aMpa]										*!					*							7.0%
an+pa  /anpa/[aNpa]													*!		**							17.8%
☞  an+pa  /anpa/[anpa]															***					*		43.4%
an+pa  /ampa/[ampa]											*!									*		27.9%
an+pa  /ampa/[aMpa]											*!				*		*					2.8%
an+pa  /ampa/[aNpa]											*!	*			**							0.4%
an+pa  /ampa/[anpa]					*!						*				***							0%

#### 4.6. The frequency effect

We see that faithfulness constraints tend to end up being ranked higher for the less common place value (labial) than for the more common place value (coronal):

IDENTPLACE (|p|) >> IDENTPLACE (|t|) (982 learners)  
 IDENTPLACE (|m|) >> IDENTPLACE (|n|) (968 learners)

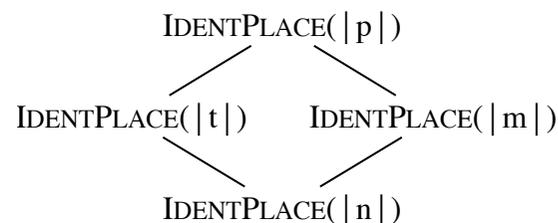
#### 4.7. The cue reliability effect

We see that faithfulness constraints tend to end up being ranked higher in an environment with more reliable place cues (plosives) than in an environment with less reliable place cues (nasals):

IDENTPLACE (|p|) >> IDENTPLACE (|m|) (953 learners)  
 IDENTPLACE (|t|) >> IDENTPLACE (|n|) (988 learners)

#### 4.8. Combined ranking by frequency and cue reliability

Not only the median learner, but 910 out of 1000 learners end up with the complete ranking that has been proposed by Boersma (1998:217) on the basis of frequency and confusability (but without simulations):



Such rankings, even if emerging automatically during acquisition, will make their influence felt throughout the phonology of the language.

#### 4.9. Universal rankings of cue constraints

Not only the faithfulness constraints, but the cue constraints tend to end up with useful rankings as well:

(1) The farther your cue is removed from the ‘best’ cue, the worse it is:

\*[p]/t/ >> \*[P]/t/ >> \*[T]/t/ >> \*[t]/t/  
\*[t]/p/ >> \*[T]/p/ >> \*[P]/p/ >> \*[p]/p/  
\*[m]/n/ >> \*[M]/n/ >> \*[N]/n/ >> \*[n]/n/  
\*[n]/m/ >> \*[N]/m/ >> \*[M]/m/ >> \*[m]/m/

(2) Adverse place cues in plosives are taken more seriously than adverse place cues in nasals:

\*[p]/t/ >> \*[m]/n/  
\*[t]/p/ >> \*[n]/m/

(3) Labial place cues are taken more seriously than coronal place cues:

\*[p]/t/ >> \*[t]/p/  
\*[m]/n/ >> \*[n]/m/

### 5. Attested (near-)universal rankings of faithfulness

Many different types of universal or near-universal rankings of faithfulness constraints have been proposed in the literature. What do these rankings reflect, and to what causes did the authors ascribe the universality of these fixed rankings?

#### 5.1. Universal faithfulness rankings reflect phonological context

Beckman (1998) proposes a universal ranking of faithfulness as a function of the phonological context (*positional faithfulness*):

IDENTPLACE(onset) >> IDENTPLACE(coda)

Beckman ascribes the universality to innateness (i.e. probably to some adaptive function during human evolution).

Cause predicted by the present model: *if* faithfulness constraints are positional (i.e. are conditioned by syllable position), *and* auditory place cues are *on average* more reliable in onset than in coda, *then* the learner will come to rank IDENTPLACE(onset) above IDENTPLACE(coda), *even if* no such ranking is evident in the parents’ productions.

#### 5.2. Universal faithfulness rankings reflect cue audibility

Steriade (1995, 2001) proposes a universal ranking of faithfulness as a function of universal cue audibility (*licensing by cue*):

IDENTPLACE(apical,coda) >> IDENTPLACE(apical,onset)

Steriade ascribes the universality of these rankings to extralinguistic knowledge of the universal auditory distance between phonological candidates (‘P-map’).

Cause predicted by the present model: *if* faithfulness constraints are as granular as Steriade proposes, *and* apicality cues are better in coda than in onset, *then* the learner will come to rank IDENTPLACE(apical,coda) above IDENTPLACE(apical,onset), even if her parents do not.

### 5.3. Universal faithfulness rankings reflect confusability

Boersma (1998 et seq.) proposes a universal ranking of faithfulness as a function of language-specific confusability:

IDENTPLACE(|p|) >> IDENTPLACE(|m|)  
IDENTPLACE(|t|) >> IDENTPLACE(|n|)

Boersma ascribes the universality to explicit linguistic knowledge of confusion probabilities (computed by running auditory forms through the language's perception grammar many times).

Cause predicted by the present model: a side effect of learning.

### 5.4. Universal faithfulness rankings reflect frequency of occurrence

Boersma (1998: 180–184) proposes a universal ranking of faithfulness as a function of frequency of occurrence (*markedness*):

FAITH (+round) >> FAITH (–round)  
because [+round] is less frequent than [–round]

Boersma ascribes the universality to emerge from the workings of an unspecified learning algorithm (*specification strength*).

Cause predicted by current model: a learning algorithm indeed. The proximal cause is in the automatic and implicit influence of frequency on learning (given this learning algorithm), and the distal cause (the one that caused the frequency difference in the first place) is probably in the phonetics (rounding tends to obscure auditory contrasts).

### 5.5. Conclusion

Although all previously proposed universal faithfulness rankings can be said to have their distal and/or proximal causes in the phonetics, all the proposed explanations can be dispensed with. Thus, we can dispense with: innate ranking (e.g. by position), extralinguistic knowledge (e.g. the P-map), and explicit computation (e.g. of confusion probabilities).

## 6. Discussion

### 6.1. Summary (copied from the abstract)

Computer simulations show that even if generation 1 has all faithfulness constraints top-ranked, we need assume no more than a fixed background (or transmission) noise to ensure that the learners of generation 2 will rank faithfulness by both average cue reliability (e.g. slightly higher for plosives than for nasals) and by frequency (e.g. slightly higher for labials than for coronals). Depending on how finely grained the faithfulness constraints themselves are contextualized, one will also find licensing by cue and/or positional faithfulness (e.g. faithfulness ranked higher for onsets than for codas), leading to the well-known observed triple asymmetries (by place, manner, and position) in nasal place assimilation. These findings show that non-goal-oriented mechanisms (theoretically required by e.g. Ohala 1981 and Blevins 2004) can account for seemingly goal-oriented phenomena (which are observed facts).

### 6.2. Evolution over the generations

The shift between Generations 1 and 2 found in §4.5 does not lead to a language that is stable over the generations: when the outputs of Generations 2 and up are filtered with the same transmission noise as those of Generation 1, the auditory contrast between underlying labials and coronals will be washed out within a few generations.

To ensure stability over the generations, some simplifications have to be undone: parallel comprehension has to be replaced by modular comprehension (McQueen & Cutler 1997), and the learning algorithm of parallel virtual production has to be supplemented with lexicon-driven learning of prelexical perception (Boersma 1997, Escudero & Boersma 2003), which produces a prototype effect that ensures stability over the generations, at least if the articulatory constraint is split up into multiple categorical ones (Boersma & Hamann 2006).

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